A STRATEGY TO IMPROVE THE EARLY PRODUCTION PHASE IN AIR FORCE ACQUISITION PROGRAMS

Allen D. Lee

December 1983

ADA 152 542

THE RAND GRADUATE INSTITUTE
FOUNDED 1970
CALIFORNIA

P-6941-RGI

Ø-DTIC

The Rand Paper Series

Papers are issued by The Rand Corporation as a service to its professional staff. Their purpose is to facilitate the exchange of ideas among those who share the author's research interests; Papers are not reports prepared in fulfillment of Rand's contracts or grants. Views expressed in a Paper are the author's own and are not necessarily shared by Rand or its research sponsors.

The Rand Corporation, 1700 Main Street, P.O. Box 2138, Santa Monica, CA 90406-2138

A STRATEGY TO IMRPOVE THE EARLY PRODUCTION PHASE IN AIR FORCE ACQUISITION PROGRAMS

Allen D. Lee

December 1983

The original version of this study was prepared by the author, Allen D. Lee, as a dissertation in partial fulfillment of the requirements of the doctoral degree in policy analysis at The Rand Graduate Institute. It was approved by Dr. Lee's dissertation committee on May 28, 1981.

PREFACE

This Paper constitutes a dissertation in partial fulfillment of the requirements for a doctoral degree from The Rand Graduate Institute of Policy Analysis. The research has evolved from work undertaken within the previous Rand R&D and Systems Acquisition Program. It has been completed under a Project AIR FORCE study project "Air Force Acquisition Options for the 1980s." It addresses issues of designing the early production phase in major systems acquisition programs to reduce costs and improve system effectiveness. It parallels a report being prepared for the Air Force: *Cost Effects of Phased Acquisition During Early Production*, R-2593-AF. Both reports follow from a long-term concern at Rand with acquisition strategies that might offer improvements in the cost, schedule, and system performance outcomes of major weapon acquisition programs. This dissertation was presented to The Rand Graduate Institute Academic Advisory Board in a briefing on May 2, 1981.

ACKNOWLEDGMENTS

Several people contributed in very important ways to the completion of this dissertation and I would like to take this opportunity to express my special thanks to them.

At The Rand Corporation, this work benefitted extensively from the contributions of Robert Perry who provided the initial concept and stimulus and the long-term support which brought this effort to fruition. I would also like to thank Michael Rich for his support and technical contributions during the later stages of this research. The quality, utility and validity of this research benefitted from the technical suggestions and contributions by my colleagues at Rand: Giles Smith, William Stanley, Jean Gebman, Edmund Dews, and Dick Nelson. Patricia Dey and John Schank also deserve thanks for their assistance in locating and compiling crucial data for the analyses.

Col. John Mantei, in Air Force Systems Command at Wright-Patterson Air Force Base, provided extensive assistance and support in developing the F-15 data base. He deserves special thanks for his cooperation and interest. I would also like to thank Maj. Nelson Noell, of the same office, for his valuable assistance.

This effort would not have been possible without the long-term support of Charles Wolf, Jr., Dean of The Rand Graduate Institute, and his quick assistance during the inevitable crises in completion of this work. I would also like to thank Carol Tripp, Dr. Wolf's assistant, for her many rescues and words of encouragement.

My dissertation committee members--Arthur Alexander, Arturo Gándara, and Bruce Goeller--deserve my sincere gratitude for their valuable comments and suggestions. Their extensive contributions of time and energy greatly enhanced the quality of this research. I extend special appreciation to Arthur Alexander, my committee chairman, for his substantial contributions to designing the analytic approach employed in this dissertation.

Finally, I dedicate the energies I devoted to this work to the memory of Joan Douglas. She typed the original manuscript in her

accustomed flawless manner and provided useful editorial comments. Her giving attitude and the pride she took in doing good quality work made my task much easier.

The quality of this work benefitted significantly from the contributions of each of these individuals. Any errors or oversights, however, remain my responsibility.

CONTENTS

FIGURES

TABLES

I. IDENTIFYING THE PROBLEM AND DEVELOPING A SOLUTION

A. RESEARCH ISSUE AND CONTEXT

Many new major weapon systems enter production with immature designs that provide less effectiveness and generate higher maintenance costs than anticipated. In the long-run, the military must either accept reduced effectiveness and higher costs or mature the design through design modifications. One proposed approach for providing mature systems in a cost-effective manner recommends (1) extending the initial, low-rate production phase, (2) intensifying early testing and operations, and (3) using test and operating data quickly to develop design modifications. This dissertation investigates the characteristics of such an approach, the conditions which favor its application, and the potential costs and benefits of applying the approach in the Air Force context.

Though this dissertation focuses on only Air Force programs, the implications need not be restricted to the Air Force context alone. The problems of design immaturity arise in the commercial sector as well. Recent, major automobile recalls and bus structural modifications, for example, illustrate that commercial products may also require design changes after entering production. And, the Navy and Army have faced reduced effectiveness and increased costs when their systems entered production prematurely. Thus, though this dissertation relies on Air Force experience only, it presents observations of wider interest.

The decision to develop a new product and the decision to purchase and operate it depend on its known and estimated costs and benefits. The new product may provide services that previous products could not, or it may provide available services more effectively; additionally, the new product may have reduced production, operating, or maintenance costs. The services provided by a product constitute its direct benefits. The product requires expenditures from initial product development, through production, and throughout operational use, as shown in Fig. 1. In general, different actors pay the various costs, whereas only the product user reaps direct system benefits.

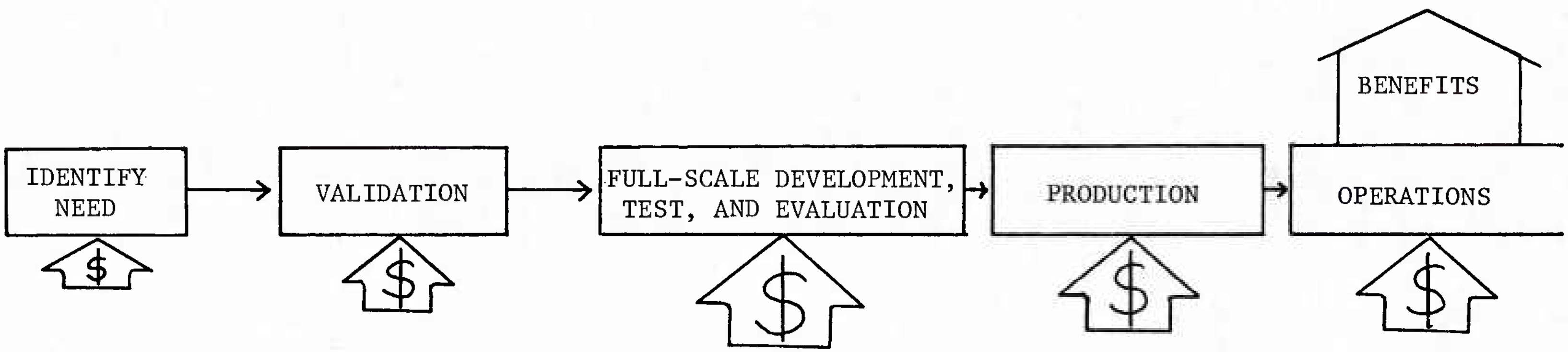


Fig. 1--Conceptual view of the new product life cycle

In Air Force programs, while funds for system development, production and operations come out of the total Air Force budget, individual commands usually face but one or two of these costs. Only the operating command receives the direct system benefits. From the perspective of Air Force Headquarters and the Department of Defense (DoD), however, each system warrants evaluation of all its costs and direct and indirect benefits. This more inclusive viewpoint requires that high-level decisionmakers consider all potential costs and benefits from system development through day-to-day system operations.

The large magnitude of system costs and benefits, throughout the entire system lifetime, requires that the Air Force carefully track the record of major systems. The total system costs from design through retirement constitute system life cycle cost (LCC). The benefits produced by the system are usually called system effectiveness. To a substantial degree, early design and development decisions predetermine the magnitudes of system production, operating, and maintenance costs and system effectiveness. Any buyer who contracts for development and production of a new product, as DoD and the Air Force usually do, has the incentive to insure that the product design reflects concern for future costs and effectiveness, as well as near-term costs of development and production.[1,2]

Table 1 shows how the DoD and Air Force distribute their system acquisition and support budgets. It shows FY 1981 obligations for RDT&E (Research, Development, Test, and Evaluation), procurement, and O&M (Operations and Maintenance). Both budgets allocate the least, around 20 percent of system acquisition and support expenditures, to RDT&E. Both allocate roughly 40 percent to both procurement (production) and O&M. In real terms, O&M expenditures have increased over 80 percent, while overall DoD expenditures have increased only about 25 percent since 1955. This trend towards higher proportional O&M expenditures has received increasing attention in the military, executive agencies, and Congress.

Often because of high O&M costs, Air Force systems undergo design modifications. Modifications also occur to improve effectiveness

---

[1]This contrasts with the purchase of an off-the-shelf item where the buyer has no influence on product design and development.

[2]Note that the Air Force, in trying to obtain project funding, also has a strong incentive to underestimate long-run costs.

and correct deficiencies. The modification process frequently represents additional development, necessitated by the immaturity of system designs that have gone into production. Modifications may entail both production-line changes and retrofit of systems already produced and operating. Out of the Air Force FY1981 budget, \$1.4 billion has been allocated for modifications. This equals about 10 percent of the Air Force procurement budget and 20 percent of the RDT&E budget.

When systems require large amounts of maintenance or have performance deficiencies, their effectiveness suffers. Modifications may reduce these problems, but the Air Force often cannot afford to conduct all desirable modifications. Consequently, the Air Force may have to choose effectiveness reductions over increased modification expenditures. Recent publicity regarding the limited operational capability of the major Air Force and Navy fighter aircraft, the F-15 and F-14,

Table 1

FY81 BUDGET OBLIGATIONS (\$B)

	RDT&E	Procurement	O&M
DoD	16.19	42.12	45.26
Air Force	7.39	14.36	13.11

SOURCE: *The Budget of the United States Government*, U.S. Government Printing Office, Washington, D.C., 1980.

indicates the existence of a major effectiveness problem. As recently as late in 1978, less than 40 percent of the Air Force F-15s, costing nearly \$20 million apiece, achieved fully mission capable status.

Figure 2 depicts the activities in a typical, conventional military system life cycle. The figure presents the activities as they occur over time, from left to right. It shows the flow of resources into each activity and the flow of benefits from the operations phase. The figure specifically identifies the modifications phase; in a sense, this phase represents a continuation of the full-scale development

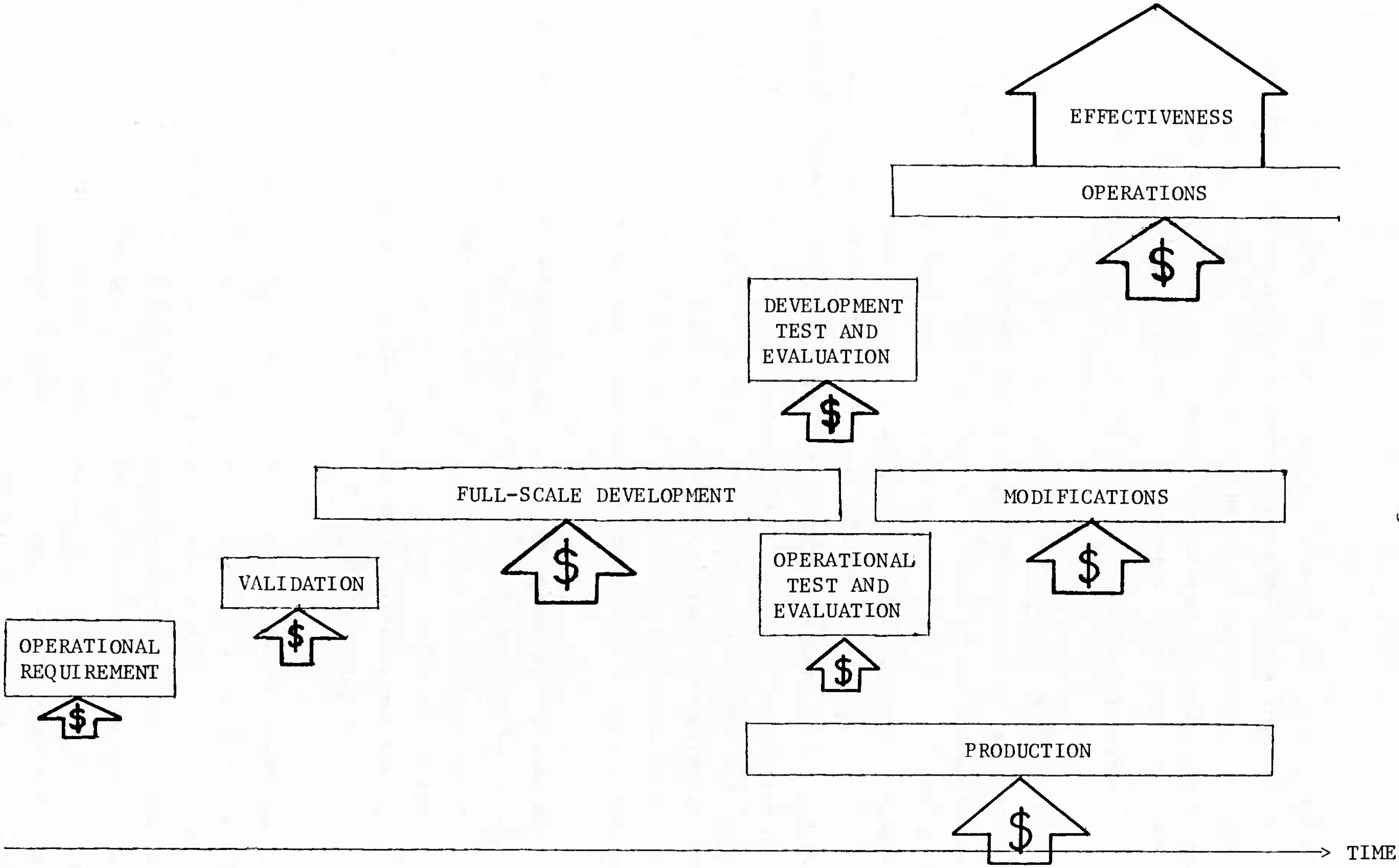


Fig. 2--Typical conventional military system life cycle

The detailed steps in the life cycle showing their typical sequencing and concurrency and the input of resources and output of system effectiveness.

phase since it comes about because systems from the production line have immature, or incompletely developed, designs. The figure shows considerable overlap, or concurrency, between validation and full-scale development, and among full-scale development, production, and the two test phases. Previous experience and research have suggested that such concurrency increases program costs and reduces system effectiveness.

B. DISSERTATION FOCUS, RELEVANCE, AND PURPOSE

This dissertation focuses on the following question: *Given a specific system design at the end of initial development and a set of required design modifications, how can the transition from development to production be structured to accomplish these modifications at minimum life cycle costs for a given aggregate effectiveness level?* The previous discussion has suggested that system life cycle costs and effectiveness depend significantly on activities early in the life cycle. This dissertation explores specifically how modification costs and system effectiveness depend on parameters defining the development-production transition phase. And, it explores what parameter values would optimize program cost-effectiveness. This research addresses the following four basic questions:

1. How does system design maturity affect program cost-effectiveness?
2. How do early production phase strategies affect design maturity?
3. How can planners change the early production phase to improve program cost-effectiveness?
4. What are the implementation implications of such improved early production phase strategies?

This dissertation has relevance to previous Rand research and recent federal acquisition policies. They have recommended in recent years an acquisition strategy incorporating less concurrency, early tests and demonstrations, increased use of test data in the development process, phased decisionmaking, and delayed commitments to high-rate production until system maturity has been demonstrated. In this dissertation, I designate this approach the *Phased Acquisition Strategy or PAS*. Figure 3 illustrates the strategy. This figure shows the key phases

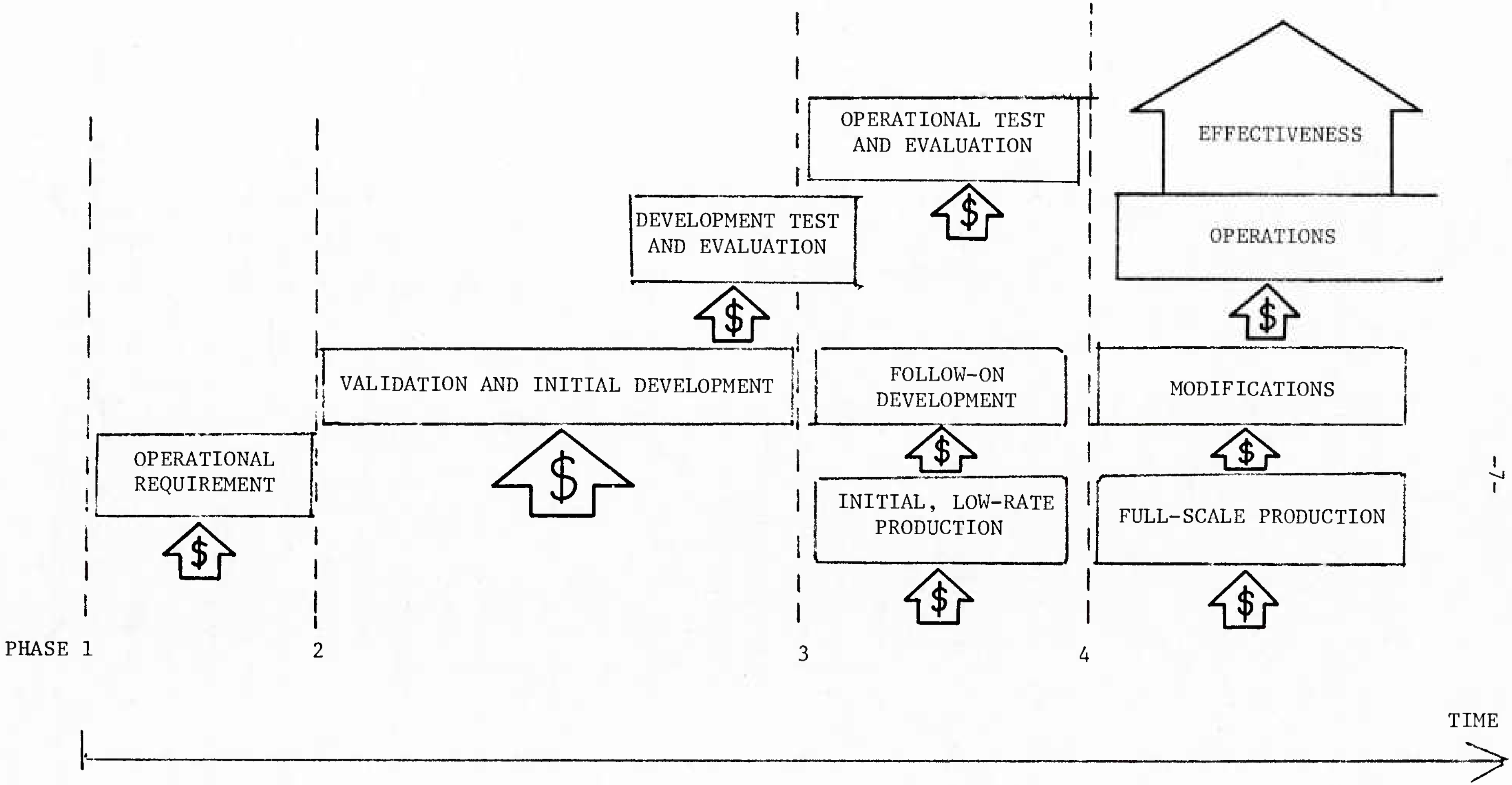


Fig. 3--Phased acquisition strategy and life cycle activities in the typical phased acquisition program, key phases, resource flows, and effectiveness output.

beginning at the start of the operational requirement, through the validation and initial development, initial low-rate production, and full-scale production phases. PAS breaks development into two phases--the first leads to an initial system design for low-rate production and early operating tests, and the second leads to a mature design for full-scale production. Section III discusses the other features of the strategy in detail. This research provides partial answers to the questions of when and how to apply the PAS approach and what effects it will produce.

The research results should benefit acquisition policymaking. At the least, this dissertation illuminates some of the relationships between features of the transition from development to production and modification costs and system effectiveness. Aware of these relationships, policymakers can establish acquisition policies with better knowledge of the consequences for modification costs and system effectiveness. This dissertation also provides initial information about what acquisition strategy features may benefit different types of programs. Program decisionmakers could use this information to design an acquisition strategy more nearly tailored to the features of individual programs.

C. STEPS IN ANALYSIS

This analysis consists of several steps. This sub-section describes the five basic analytic steps.

Review Acquisition Experience, Research, and Policies

Acquisition research has addressed issues such as structuring development, minimizing production costs, and measuring program outcomes. Past research, in general, has studied various aspects of the military-system life cycle in an effort to illuminate how the acquisition process affects program outcomes.

Policies promulgated and instituted by DoD, OMB, and the services have attempted to change the acquisition process to reflect the findings of acquisition research studies. They have attempted to improve program outcomes by instituting changes that research has suggested would be beneficial.

Recent policies, drawing upon experience and research results, have tended to emphasize acquisition strategies which avoid production of immature systems. They recognize the potential for large O&M costs when production systems have unproven designs. They recognize the possibility of serious effectiveness deficiencies with immature designs. Recent policies have instituted strategies requiring early and recurrent evaluations of life cycle costs and system effectiveness, early tests and demonstrations, incremental decisionmaking and commitments, and continuous evaluations of tradeoffs among system cost, schedule, and performance. The PAS approach represents one acquisition strategy, evolving out of Rand research, that also incorporates these concepts and practices.

This dissertation relies on past acquisition research to address the issue of how an acquisition strategy affects modification costs and system effectiveness. It uses the information contained in that body of work to generate a general framework of the system life cycle process.

Develop Life Cycle Models

The general life cycle model breaks the life cycle into initial development, follow-on development, initial production, initial operations, maintenance and support, full-scale production, modifications, and full-scale operations. Conventional descriptions of the life cycle include most, but not all, of these processes. The breakdown here emphasizes the underlying necessity for sequential activities in an acquisition program. And, it manifests the links between early and succeeding activities.

The general model defines the output of the acquisition process and establishes its dependence on decisions and activities during acquisition. It relates effectiveness to the performance, reliability, and maintainability of individual systems and the number of systems produced. It then links these characteristics to preceding activities.

The general model provides a comprehensive set of activities and relationships from which to select those of primary interest in this study.

The narrowed model specifically addresses the relationships among three acquisition activities--initial production, follow-on development, and full-scale production--and the modifications process and system effectiveness. It includes specific cost functions that apply to each activity. These activities bound the scope of the study, which treats all other activities and their effects as given.

Use Model To Identify Promising Strategies

The narrowed model provides a framework for revealing the effect of acquisition program parameters on modification costs and system effectiveness. With suitable assumptions about the cost functions, the model allows us to determine acquisition parameter values that will optimize program outcomes from a cost-effectiveness perspective and to characterize promising strategies.

Conduct Case Studies

This dissertation relies on actual Air Force program experiences to provide the information for developing the theoretical models. It then returns to actual programs to explore the relevance and implications of the models. Case studies of the C-5A and F-111--developed in the mid-1960s--and the F-15--developed in the early 1970s--illustrate acquisition strategies employed in actual Air Force programs and their modifications and effectiveness consequences.

The case studies permit one to explore the acquisition parameters and relationships highlighted by the model. The case studies also demonstrate the usefulness and limitations of the model for designing improved acquisition programs.

Determine Feasibility of Implementing Promising Acquisition Strategies

This analysis raises issues about the feasibility of implementing the improved acquisition strategies. A comparison of features of the promising strategies considered in the case studies with features of actual programs illuminates potential problems in designing and implementing promising strategies. And, a review of current policies and practices permits one to assess the compatibility between current policies and promising strategies.

D. DESCRIPTION OF FOLLOWING SECTIONS

The second section reviews relevant acquisition experience, research, and policies from 1950 through the 1970s. Section III develops a general life cycle model and a narrowed model extracted from the former. The narrowed model focuses on the research topic of this dissertation. Section IV develops the narrowed life cycle model further and uses it to explore a promising acquisition strategy. Sections V through VII present case studies of three Air Force programs in light of the insights and information provided by the narrowed life cycle model. Section VIII presents a discussion of some policy issues related to acquisition strategies and the promising strategy explored earlier. The final section presents conclusions and summarizes the implications of the models, case studies, and policy issues.

II. REVIEW OF ACQUISITION EXPERIENCE, RESEARCH, AND POLICIES

A. THE RELATIONSHIP AMONG ACQUISITION EXPERIENCE, RESEARCH, AND POLICIES

Acquisition research has the purpose of developing acquisition strategies that would improve program outcomes. It relies on experiences from different acquisition programs using different acquisition approaches to infer the effects of acquisition policies on program outcomes; and it attempts to isolate these effects from the effects of factors such as the general economy, political decisions, and others. Findings from acquisition research frequently form the basis for future acquisition policies.

Thus, acquisition policymaking occurs through an iterative process drawing upon prior acquisition experiences and research findings. Tracing Air Force acquisition experience, research, and policies from the 1950s to the present establishes the context in which present Air Force acquisition occurs.[1] It also provides the background from which the models developed here have been drawn.

B. AIR FORCE ACQUISITION IN THE 1950s

Acquisition Policies and Experiences

Aircraft programs prior to the 1950s often paid minimal attention to system integration and relied on competition among alternative aircraft prototypes to produce a superior system. Fairly modest technology advances made it possible to select off-the-shelf subsystems, with a proven history, and incorporate them in new airframes. Prototyping allowed the military to support multiple, low-investment system alternatives from which they selected a preferred design.

---

[1]Though arbitrary and not indicative of a ten-year periodicity in acquisition experiences, the breakdown by decades here has proved convenient and consistent with earlier research.

The rapid technology changes of the early 1950s and a concurrent requirement for rapid system deployment shaped the acquisition approaches of the 1950s. The weapon system approach, in which the entire system is designed as a unit, resulted from pressures of rapidly changing technologies, mission needs, and environments.[1] The Cook-Craigie Plan originated, in part, as a reaction to the perceptions of some acquisition decisionmakers that the conventional prototyping approach took too long.[2] The Cook-Craigie Plan called for

- o early buildup of the production facility,
- o limited initial production,
- o elimination of system deficiencies through test flights, and
- o accelerated full-scale production thereafter.[3]

This strategy offered the possibility of high-rate production of new systems, but its originators cautioned that it warranted application only in programs where production systems would require only modest modifications.

The debut of the Cook-Craigie Plan failed to fulfill its promise. Late in 1951 the F-102 fighter program began, following the guidelines of the Cook-Craigie Plan. However, misjudgment of the adequacy of the F-102 design led to a series of major design changes to reduce weight and drag after substantial commitments had been made to production facilities. Each of two resultant major retooling efforts

---

[1] Johnson, L. L., *The Century Series Fighters: A Study in Research and Development*, The Rand Corporation, RM-2549, May 20, 1960.

[2] Marschak, Thomas, Thomas Glennan, Jr., and Robert Summers, *Strategy for R&D: Studies in the Microeconomics of Development*, Springer-Verlag, New York, 1967, pp. 103-104.

[3] Knaack, Marcelle, *Encyclopedia of U.S. Air Force Aircraft and Missile Systems, Vol. I*, Office of Air Force History, Washington, D.C., 1978.

individually scrapped over half the tools on the production line and caused significant delays in aircraft deliveries.[1] These costly program problems probably resulted largely from the demanding requirements of the F-102 performance goals and the failure of program decisionmakers to match the acquisition strategy to these requirements.

The F-100 program used a similar approach but fared somewhat better. The program employed a considerable amount of concurrency between development and production and committed resources to production early in the program. The program quickly delivered production aircraft with acceptable characteristics. Serious stability problems plagued the aircraft in later years and necessitated a major modification. On the whole, however, this program appears to have been reasonably successful. Its success probably stemmed in large part from the fairly modest technical advance required in its design and the ability of its builder, North American Aviation, to transfer learning from its precursor, the F-86.[2]

The F-104 program also proved to be generally successful. The Air Force favored a cautious approach in this program and decided to use a "fly-before-you-buy" strategy; i.e., the Air Force initially programmed procurement of only 17 F-104s for development testing before making a significant production commitment.[3] When the production go-ahead occurred, F-104 production quickly and successfully followed. The major F-104 problem stemmed from its unproven engine. The general success of this program, even though the F-104 represented a significant capability advance, appeared to result from the fairly conservative development strategy, delayed production commitment, and the experience of its builder, Lockheed, with its experimental predecessor, the F-90.

The Air Force testing procedure utilized during the early 1950s

---

[1] Johnson, pp. 21, 24.

[2] Johnson, pp. 48-49.

[3] Knaack, p. 176.

appears to have been very comprehensive, but not well-integrated. It consisted of a seven-, and later eight-, phase procedure to evaluate different system characteristics. The concept proved to be too cumbersome, decentralized, and costly and failed to provide timely information on system deficiencies. This approach, it appears, failed to provide early warnings of system deficiencies that would eventually reduce system effectiveness.[1,2]

Acquisition Research

The acquisition research of the 1950s drew its lessons from the acquisition experiences of the decade and laid the foundation for future research. A 1958 report by Burt Klein et al. established the basic concepts, issues, and tradeoffs of concern to the acquisition community over subsequent years.[3] This Paper emphasized the advantages of pursuing several viable alternatives until testing proved system performance and capability characteristics. The basic research objective of this and related research consisted of devising techniques to estimate the costs and benefits of alternative system designs. Research into parallel research and development (R&D) approaches helped quantify the benefits of pursuing more than one design alternative, thus preserving choices while accumulating more information.[4]

Summary of the 1950s

Many lessons from acquisition activities of the 1950s have

---

[1] Hersman, Maj. Walter, *Operational Testing and Evaluation in the Acquisition of USAF Weapon Systems*, Air Command and Staff College Research Study, May 1972.

[2] Dolan, Lt. Col. William, *Operational Test and Evaluation--The Key to Credibility*, Air War College Professional Study No. 4896, April 1973.

[3] Klein, Burt, W. H. Meckling, and E. G. Mesthene, *Military Research and Development Policies*, The Rand Corporation, R-333, December 4, 1958.

[4] Nelson, R. R., *The Economies of Parallel R and D Efforts: A Sequential-Decision Analysis*, The Rand Corporation, RM-2482-PR, November 12, 1959.

relevance to the research issue of this dissertation. In terms of acquisition program experiences

- o immature and unproven designs led to costly tooling changes, performance shortfalls, and delayed system availability;
- o chances for program success increased when concurrency was minimized, tests and demonstrations were emphasized, and the system design drew upon previous designs; and,
- o features of the system being developed should influence the proper choice of acquisition strategy.

In terms of acquisition policies, the decade exhibited

- o acquisition strategies that ranged from the conservative, "fly-before-you-buy" approach to the optimistic, highly concurrent Cook-Craigie Plan, and,
- o testing procedures that failed to identify production-system problems because of their lack of timeliness and proper emphasis.

And, the 1950s provided a research foundation that

- o emphasized the need for maintaining and exploring design alternatives before making production commitments; and,
- o placed the acquisition process in a cost-benefit context.

C. AIR FORCE ACQUISITION IN THE 1960s

Acquisition Research and Policies

Acquisition research in the 1960s expanded upon the themes from the previous decade, and employed increasingly sophisticated analytic techniques. One major study emphasized (1) the role of uncertainty in the weapons

acquisition process, (2) the importance of designing each acquisition program to meet the technology needs of the desired system, and (3) the importance of tradeoffs in the acquisition process. It identified two crucial needs in program decisionmaking: "good, fairly dependable data; and a thoroughgoing analysis of the data which recognizes the interactions among time, quality, cost, and value variables...."[1] Another study explored the use of prototypes as one way to gain quick, dependable information on system characteristics as a means for reducing uncertainties.[2] The study found that expedited prototyping--testing incomplete, but representative, systems quickly--offered hedges against strategic and technological uncertainties with probable cost savings compared to the conventional development-production approach--large early commitments to development and production of a given system. Other analyses pursued the issues of defining, measuring, and trading-off various characteristics that determine the value, or effectiveness, of systems.[3] These analyses set the stage for later studies that would consider the acquisition process in a cost-effectiveness context. Subsequent studies reflected the growing awareness that early decisionmaking and uncertainties played large roles in driving program outcomes. Researchers directed their techniques toward measuring and predicting risk in acquisition programs and incorporating risk assessment in decisionmaking. One analysis used subjective probability judgments and Monte Carlo procedures to develop measures of program progress.[4] Another used mathematical programming approaches to optimize development planning based on tradeoff analyses.[5]

---

[1] Peck, Merton, and Frederic Scherer, *The Weapons Acquisition Process: An Economic Analysis*, Harvard University, Boston, 1962, p. 593.

[2] Glennan, T. K., Jr., B. H. Klein, and G. H. Shubert, *The Role of Prototypes in Development*, The Rand Corporation, RM-3467-PR, April 1963.

[3] See, for example, K. L. Deaver and J. J. McCall, *An Analysis of Procurement and Product Improvement Decisions*, The Rand Corporation, RM-3859-PR, December 1963.

[4] Timson, F. S., *Measurement of Technical Performance in Weapon System Development Programs: A Subjective Probability Approach*, The Rand Corporation, RM-5207-ARPA, December 1968.

[5] Zschar, E. V. W., *Project Modelling: A Technique for Estimating Time-Cost-Performance Trade-Offs in System Development Projects*, The Rand Corporation, RM-5304-PR, July 1969.

In the 1960s, the importance of cost-effectiveness analysis became established in acquisition programs through DoD directives. Secretary of Defense McNamara took an active role in implementing new policies designed primarily to control acquisition costs, while delivering production systems in a timely manner. To control acquisition costs across the services, DoD stressed the use of derivative systems. To deliver systems rapidly and at controlled acquisition costs, DoD instituted Total Package Procurement (TPP). Also called the Charles Plan after its originator Robert Charles, then an Assistant Secretary of the Air Force, TPP required the contractor to bid on both development and production, rather than each phase separately. While conceptually requiring the contractor to deliver systems on time and at a given cost, TPP permitted the contractor considerable flexibility in making design tradeoffs.

Acquisition Experiences

Air Force acquisition experience with the C-5A cargo aircraft showed, dramatically, the flaws in the TPP approach. Since TPP almost necessitated extensive development-production concurrency and virtually eliminated alternative system designs before development began, the production C-5A incorporated design deficiencies which late tests had not yet revealed.[1] The C-5A program, in addition, experienced substantial cost overruns and effectiveness shortfalls. The major deficiency, understrength wings, has led to a very costly modification program now underway. This dissertation examines this program in more detail later.

The F-111 program also suffered excessive cost overruns and effectiveness shortfalls. Not only did the F-111 acquisition program contain a high degree of concurrency, but the requirements of the aircraft itself demanded significant technology advances in many areas. In the interests of avoiding duplication and, therefore, reducing total aircraft acquisition costs, Secretary McNamara had pursued the F-111 as a joint Navy-Air Force fighter; however, in the

---

[1]Rice, Berkeley, *The C-5A Scandal,* Houghton Mifflin Co., Boston, Mass., 1971.

F-111 debates the participants reached agreement on only one issue: "the formal performance requirements of the Air Force and Navy were impossible to meet within the technical state of the art in the 1960s."[1]

Two other programs in which the Air Force and Navy used derivatives of a common aircraft seemed to fare better. The Air Force A-7D attack aircraft evolved from the Navy A-7A. The A-7D, however, incorporated significant design changes in the engine, gun, avionics, and survivability features.[2] Though these particular subsystems have created fairly significant operational problems, the A-7D has been a relatively successful program. The Air Force also derived a fighter, the F-4C, from a Navy design. This program required only about 20 months from program go-ahead, in March 1962, to deliver the first aircraft for operational service. Though the F-4C and subsequent Air Force models have not been without problems, the Air Force has procured over 2,500 aircraft and the program must be rated relatively successful.

While taking advantage of existing designs may have been partially responsible for the success of some aircraft programs of the 1960s, new testing procedures probably played a role also. Dissatisfied with the eight-phase test procedure of the early 1950s, the Air Force replaced it with a simplified category system in 1957. Category I testing covered primarily subsystem development, and was conducted principally by the contractor with occasional Air Force participation. The Air Force conducted Category II, system development test and evaluation, with contractor participation. Category III testing addressed operational characteristics under the responsibility of the operating command.[3] Though the new testing procedure did not guarantee that adequate development or operational testing would occur before full-scale production began, or that test

---

[1] Coulam, Robert, *Illusions of Choice*, Princeton University Press, Princeton, N.J., 1977, p. 83.

[2] Nelson, J. R., P. K. Dey, M. R. Fiorello, J. R. Gebman, G. K. Smith, and A. Sweetland, *A Weapon-System Life-Cycle Overview: The A-7D Experience*, The Rand Corporation, R-1452-PR, October 1974.

[3] Hersman.

information would be properly used, the category system did decrease complexity and increase emphasis on operational testing relative to the prior phased test procedure.[1]

Summary of the 1960s

These acquisition activities that occurred in the 1960s provide lessons that relate to the research issue of this dissertation. With respect to acquisition program experiences

- o concurrency and lack of program flexibility and alternatives resulted in cost growth and serious effectiveness shortfalls;
- o demanding performance requirements increased the risks associated with system acquisition; and,
- o program success appeared more likely if a new system was derived from a proven design.

In terms of acquisition policies the 1960s showed

- o one system can be derived from another that already performs in a different role, but a new system faces serious problems if it must be designed to perform two very different roles;
- o Total Package Procurement can lead to serious program failures if any potential exists for serious design problems to occur; and,
- o the test process changed to a simpler, better integrated one that increased emphasis on operational testing.

Finally, the decade produced acquisition research that

- o identified the importance of risk, uncertainties, tradeoffs, and early decisions in determining program outcomes;
- o emphasized the use of information gathering techniques, such as prototyping, early in the acquisition process;

---

[1] J. R. Nelson et al.

- recommended selecting an acquisition strategy suitable for providing the technology level required; and
- incorporated effectiveness explicitly in the analysis of program outcomes.

D. AIR FORCE ACQUISITION IN THE 1970s

Acquisition Research

The unfavorable experiences of the 1960s stimulated analysts to explore techniques for reducing the uncertainties facing new production systems. One study concluded "in some circumstances...the most desirable way of resolving technological uncertainty...may be to build and test a prototype."[1] This study argued that even extensive pre-production analysis and planning could not substitute for prototype testing. Other studies used two decades of military acquisition experience to relate program outcomes to the required technological advance.[2,3] One Rand Corporation study concluded that, if the acquisition strategy relied on (1) incremental activities and (2) austere development, program outcomes would probably improve because of increased options and reduced uncertainties.[4]

Air Force studies stressed similar themes. One study reviewed acquisition experience from 1940 to 1970 and concluded

> The higher the technical risk, the lower should be the initial production commitment....In the case of future programs like the B-1, it may prove better to return to the methods used in the 1950s and build a prototype

---

[1] Perry, Robert, *A Prototype Strategy for Aircraft Development*, The Rand Corporation, RM-5597-1-PR, July 1972, p. 3.

[2] Harman, Alvin, and Susan Henrichsen, *A Methodology for Cost Factor Comparison and Prediction*, The Rand Corporation, RM-6269-ARPA, August 1970.

[3] Perry, Robert, G. Smith, A. Harman, and S. Henrichsen, *System Acquisition Strategies*, The Rand Corporation, R-733-PR/ARPA, June 1971.

[4] Perry et al., June 1971.

> vehicle....Too often in the past, where there was concurrent production and development, decisions were narrowed to a choice between cancellation after large investments of time and money, and large cost increases.[1]

Another study reviewed the adequacy of reliability and maintainability (R&M) estimation and use during system design; it concluded that (1) R&M requirements often lacked appropriate definitions, (2) R&M information did not meet the needs of tradeoff analyses, and (3) R&M demonstrations failed to adequately reflect the operational environment.[2]

Studies of the 1970s expanded the bounds of analysis to explore the effects of acquisition policy on downstream system costs and system effectiveness. This expansion increased the use of LCC analysis in a cost-effectiveness context.

Life cycle analysis has received increasing attention from acquisition policy analysts. The Logistics Management Institute (LMI) conducted important early research on this topic. An LMI study from 1965 supported the use of LCC analysis as an acquisition decisionmaking tool.[3] LMI concluded that consideration of logistics effects using available, admittedly preliminary, analytic techniques would improve military program outcomes and they recommended that DoD should test LCC evaluation in actual procurements. A recent book by Blanchard describes the life cycle process, pointing out the "iceberg effect" in programs where the seen costs represent only a small portion of total costs generated by early acquisition decisions.[4] Studies have focused on specific applications of LCC analysis. One study of the

---

[1] Lusby, Col. William, Jr., "Aeronautical Systems Testing and Evaluation Procedures," Air War College, Professional Study No. 4186, November 1971, p. 15.

[2] Stover, Capt. Thomas, *An Analysis of Reliability and Maintainability in Weapon System Design*, Thesis, Air Force Institute of Technology, School of Systems and Logistics, No. SLSR-62-71B, August 18, 1971.

[3] *Life Cycle Costing in Equipment Procurement*, Task 4C-5, Logistics Management Institute, Washington, D.C., April 1965

[4] Blanchard, Benjamin, *Design and Manage to Life Cycle Cost*, M/A Press, Portland, Oregon, 1978.

A-7D aircraft suggested that high operating and support costs could have been avoided if more attention had been paid to early test data.[1] Another study of the A-7D found that historical experience, combined with initial operating data, could have produced fairly reliable estimates of system LCC.[2] Finally, a third study developed a methodology for estimating turbine engine LCC from engine performance characteristics and the technology advance represented by the engine.[3]

This focus on the life cycle illuminated issues of system effectiveness. Just as early acquisition decisions affect later operating and support costs, they also affect eventual system effectiveness levels. The relationships that analyses identified between acquisition decisions and subsequent costs helped characterize the effects of acquisition decisions on system effectiveness. A 1972 review of the initial attempts to integrate effectiveness analysis into acquisition decisionmaking, however, revealed a poor record because of "an apparent inability to consider total system costs, derive adequate measures of effectiveness and properly develop reliability requirements as an integrated part of the cost-effectiveness analysis."[4]

Research in the 1970s attempted to respond to some of these inadequacies in prior cost-effectiveness studies. An LMI study used case studies to explore the effect of early system reliability improvements on program costs and effectiveness. It concluded that an initial program cost increase of 7.8 percent, to improve reliability, could have reduced downtime and maintenance costs enough to reduce overall life cycle cost 27 percent and increase mission success probability

---

[1] Nelson et al., 1974.

[2] Fiorello, Marco, *Estimating Life-Cycle Costs: A Case Study of the A-7D*, The Rand Corporation, R-1518-PR, February 1975.

[3] Nelson, J. R., *Life-Cycle Analysis of Aircraft Turbine Engines*, The Rand Corporation, R-2103-AF, November 1977.

[4] Smith, Lt. Col. Stanley, *Critique of the Use of Cost Effectiveness Analysis during Aeronautical System Development*, Air War College, Air University, Report No. 4722, Maxwell AFB, Alabama, April 1972, p. 55.

by 54 percent.[1] Another study developed a detailed methodology for estimating the maintenance cost savings from adopting an acquisition strategy that emphasized specific techniques to reduce eventual maintenance requirements.[2] Finally, an Air Force study developed a methodology to calculate how program factors affect cost and effectiveness, and applied it to hypothetical programs.[3] The data requirements of the methodology, however, pointed out the continuing inadequacies in contemporary acquisition practices.

Acquisition Policies and Experiences

The acquisition policies of the 1970s also reflected the lessons learned from the 1960s and kept pace with acquisition research.

In keeping with the growing awareness of testing usefulness in determining program outcomes, a new Air Force testing procedure originated in 1971. A new Development, Test, and Evaluation (DT&E) phase replaced the earlier Categories I and II. The developing command assumed responsibility for this phase with operating and support command participation. The test program also instituted an Initial Operational Test and Evaluation (IOT&E) phase to provide early data about system operational effectiveness. Finally, a full-scale OT&E phase replaced the earlier Category III. This process remains in effect today.[4]

David Packard, formerly Deputy Secretary of Defense, instituted many of the major policy innovations of the 1970s. The Defense System Acquisition Review Council (DSARC) process directed system acquisition

---

[1] *Criteria for Evaluating Weapon System Reliability, Availability and Costs*, Task 73-11, Logistics Management Institute, Washington, D.C., March 1974.

[2] Johnson, W. L., and R. E. Reel, *Maintainability/Reliability Impact on System Support Costs*, Technical Report AFFDL-TR-73-152, Boeing Aerospace Co., Seattle, Washington, December 1973.

[3] Anderson, Richard, T. Dixon, Capt. R. Conch, and Lt. Col. W. Newhart, *Models and Methodology for Life Cycle Cost and Test and Evaluation Analyses*, OAS-TR-73-6, Office of the Assistant for Study Support, DCS/Development Plans, AFSC, Kirtland AFB, New Mexico, July 1973.

[4] Hersman.

toward more incremental decisionmaking with emphasis on preserving options and evaluating potential tradeoffs. Formalized in a 1971 DoD Directive, the process established the Development Concept Paper (DCP), later retitled the Decision Coordinating Paper, as the key document recording the progress of a new system.[1] The DSARC process established a sequence of milestones at which the DSARC reviewed the acquisition program and recommended to the Secretary of Defense whether or not to proceed with it. The current process includes four milestones:

- DSARC 0 -- program initiation,
- DSARC 1 -- demonstration and validation,
- DSARC 2 -- full-scale engineering development, and
- DSARC 3 -- production/deployment

Specifically, the DSARC process has established requirements for:

(1) stating and reevaluating system need in operational terms,
(2) incorporating early evaluations of LCC and logistics effects,
(3) conducting tradeoff analyses,
(4) assessing technical risk continually throughout acquisition,
(5) conducting early T&E and assessing operational suitability before commencing full-scale production, and
(6) providing essential information for management control.

While the DSARC process has instituted general acquisition policies, Packard and Defense Secretary Laird endorsed and pushed implementation of competitive prototyping as a specific acquisition initiative to achieve the goals of the DSARC approach. Prototyping, reflecting the lessons of earlier experiences, provided actual hardware test data on which to base major acquisition decisions. Competition in the prototyping activity has increased the number of design alternatives and

---

[1] DoD Directive 5000.1, "Acquisition of Major Defense Systems," March 19, 1980.

forced contractors to control costs. Major military programs that have utilized competitive prototyping include

- o the Air Force Close Air Support Aircraft, A-10, and the Lightweight Fighter, F-16; and
- o the Army Advanced Attack Helicopter, YAH-64, and the Utility Tactical Transport Aircraft System, UH-60.

The office of Management and Budget (OMB) has entered the acquisition policy arena by establishing acquisition guidelines for major system acquisitions of all Executive Agencies.[1] OMB Circular A-109, developed by its Office of Federal Procurement Policy (OFPP), has restated the key components and features of the DSARC process and introduced other acquisition policies reflecting a substantial consensus of opinion on the acquisition process.[2,3] A-109 has formulated the management objectives of major system acquisition:

(1) ensure that each major system fulfills a clear mission need and operates effectively with demonstrated performance and reliability;

(2) utilize competition, whenever economically feasible, throughout the entire acquisition process;

(3) ensure appropriate tradeoffs among all life cycle cost components, schedule, and performance;

(4) ensure adequate test and evaluation; and,

(5) tailor an acquisition strategy to suit the specific program.

The circular emphasizes several basic elements of the recommended acquisition policy by spelling out, in detail, the

---

[1]OMB Circular A-109, "Major System Acquisitions," April 5, 1976.

[2]U.S. Defense Blue Ribbon Panel, *Report to the President and the Secretary of Defense on the Department of Defense*, U.S. Government Printing Office, Washington, D.C., 1970.

[3]*Summary of the Report of the Commission on Government Procurement*, U.S. Government Printing Office, Washington, D.C., December 1972

(1) process for determining a mission need,

(2) approaches for pursuing alternative systems,

(3) process and importance of demonstrating system characteristics, and

(4) criteria for warranting proceeding to full-scale development and production.

Air Force acquisition programs of the 1970s have provided only partial information about the influence of new acquisition policies on program outcomes. The primary Air Force fighter, the F-15, entered development before the major policies completely went into effect. The program underwent a fairly thorough development and test program. However, the F-15 engine, one of the most technologically challenging F-15 subsystems, by-passed some of its stricter test requirements because of early design problems and, subsequently, caused a significant proportion of early F-15 operational deficiencies. The F-16 aircraft evolved from a plan using prototypes to explore new technologies. Though a representative of the prototype approach, the F-16 program has been complicated by issues of multi-national co-production. The A-10 resulted from a competitive prototype strategy based on the initiatives of Deputy Secretary of Defense Packard. By most accounts the A-10 program has been relatively successful.

Summary of the 1970s

In terms of acquisition activities, the 1970s witnessed most dramatically an acute awareness of the need for improved acquisition policies and increased attention to their generation. Acquisition policies of this decade reflected the lessons of the 1960s and instituted techniques designed to avoid the costly mistakes of the past. Specifically, policies of the 1970s have

- emphasized and instituted testing procedures to gain better, early information about system characteristics, particularly operational characteristics;

- o recommended competition throughout acquisition to ensure options and reduce costs;
- o instituted incremental decisionmaking at key decision points, relying on the best available test and demonstration data;
- o required the reevaluation of mission needs and system performance throughout the life cycle; and,
- o recommended maintaining flexibility in the acquisition process and tailoring the strategy to suit individual systems.

Acquisition research of the 1970s emphasized many of the issues addressed by the acquisition policies. In particular, acquisition research of the decade

- o recommended austere development and the use of prototypes to reduce uncertainties and maintain options;
- o identified the "iceberg effect" of large life cycle costs unseen during acquisition;
- o increased understanding of the role of early design decisions in determining downstream operating and maintenance costs; and,
- o provided initial analyses of the costs of early reliability and maintainability improvements and the consequent reductions in operating costs and increases in effectiveness.

Though not all the results are in, the acquisition programs of the 1970s appeared relatively successful. They seemed to reinforce lessons from the past and validate policies of the present. Specifically, acquisition experiences

- o demonstrated that technologically challenging programs, without intensive test and demonstration, risked unfavorable outcomes; and,
- o prototype approaches could provide desirable options and favorable program outcomes.

Designing Improved Acquisition Programs

While recent policies provide guidelines that describe desired acquisition strategies, they do not provide much information for designing the details of such strategies. They emphasize phased decisionmaking, reduced concurrency, increased early testing, increased use of test data, and delayed commitments to full-scale production; and, they recommend tailoring the strategy to suit individual programs. The Phased Acquisition Strategy, PAS, coincides with these guidelines and objectives. The next section describes this strategy in more detail and presents a model for analyzing it.

III. DEVELOPMENT OF TWO LIFE CYCLE MODELS--THE THEORETICAL FRAMEWORK

A. ANALYTIC APPROACH--OBJECTIVE AND OVERVIEW

This dissertation develops a theoretical model to facilitate an analysis of the Phased Acquisition Strategy, PAS. Though PAS is a general strategy incorporating increased testing, better use of test data, and delayed commitments, this research focuses on implementing the strategy only during the early production phase. In this application PAS would involve

- increased tests to identify required modifications,
- early operational tests,
- rapid use of test data to develop modifications, and
- extended low-rate production.

This research focuses primarily on the direct effect PAS would have on modification costs, other costs during early production, and system effectiveness. To satisfy this analytic scope, the theoretical model emphasizes these strategy variations and includes three steps in the process of acquiring a final design configuration--(1) development of an initial production design, (2) identification of required design modifications and their development, and (3) implementation of the design modifications to bring the initial production design up to the final design configuration. In effect, this framework explicitly captures the implicit continued development effort that occurs after the end of the nominal development phase in most weapons programs.

To adequately describe this process, this research has produced two theoretical models, one nested within the other. The first represents the abstracted features of the general life cycle process. It utilizes general functional relations of selected variables to illustrate what program variables affect each major cost category. The second model uses the same basic structure but within a more limited scope and with greater detail in functional specifications. This

limited model--the focus of this dissertation research--encompasses the system effectiveness and modification cost effects of acquisition activities during the transition from development to production. We note that, as with any model, this model presents only a partial picture of reality and may require certain changes when applied to actual cases.

This analysis requires specific definitions of the various life cycle processes. Figure 4 illustrates the processes included in the proposed framework.

The first phase, initial development, includes design work, paper studies, analysis, hardware development, testing programs, and all other efforts that lead to an initial production design. It does not include planned development which takes place after production of the initial production design begins. In some cases it may include prototype construction and testing. Initial development has the objective of designing, for initial production, a system which has specified characteristics and production costs.

At the end of initial development the initial production phase begins. It involves production of systems based on the initial design. The model includes this phase to (1) allow for an opportunity to make design modifications required by changed requirements, system deficiencies, or revised tradeoffs between characteristics, (2) provide the option of incremental development, and (3) permit an opportunity to gather operating data.[1] The model assumes that *system production costs during this and the subsequent production phase depend only on the initial production design.* Any additional production costs, because of design changes, will be captured by the modification process discussed later.

During the initial production phase, follow-on development occurs to validate system characteristics, identify desired changes, and develop appropriate modifications. The extent of this development effort depends on the magnitude of system changes required and the

---

[1]In some cases minimum life cycle costs might result if initial development were so thorough and complete that neither the first production phase nor subsequent development was required.

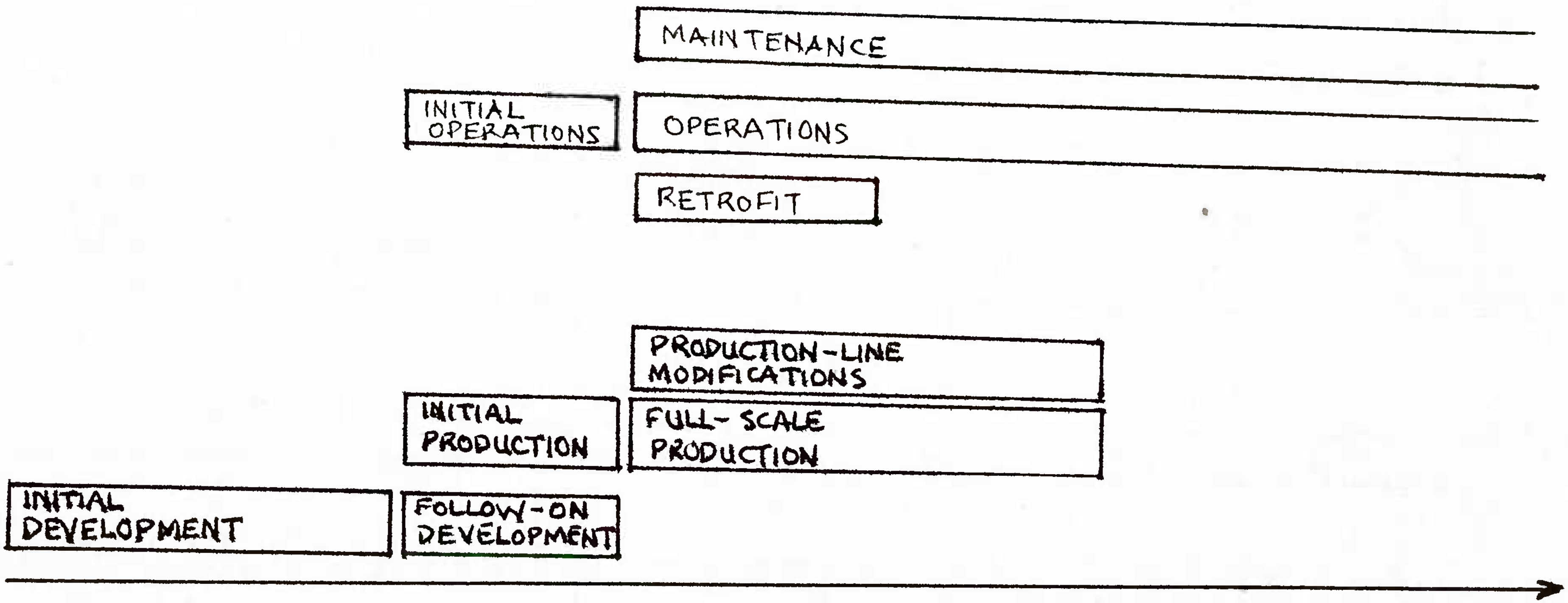


Fig. 4--Life cycle activities included in the general life cycle model

schedule of the development program. Generally, expenditures during this development phase would increase for either a very compressed or very extended development schedule; some intermediate phase length would minimize associated costs. The model also allows for these development expenditures to be reduced by accumulating operating experience on systems as they are produced since operating experience can both generate data which help define required modifications and substitute for more standard development activities.

Once the desired modifications have been defined and designed, the second, or full-scale, production phase begins. Within this framework, the production process remains the same as during the first production phase, but the production rate may vary.[1] Second-phase production costs depend on the production rate, production quantity, and system initial-design characteristics.

This framework attempts to avoid any obfuscation of the true magnitude of modification costs by distinguishing carefully between the costs of producing the initial design and the costs of incorporating modifications on the production line. The model assumes that the *production process* results in the same system design during both initial and full-scale production. However, during full-scale production the design may change as a result of production-line modifications. The model treats all the additional costs associated with these production-line design changes as production-line modification costs. All systems produced during the initial production phase undergo the same design modifications, but on a retrofit basis. The retrofit cost category captures all these costs.

The model also includes the maintenance activity. A user incurs maintenance costs from the time the first system begins operating until the last system retires. Though annual system maintenance costs may be small compared to acquisition costs, cumulative lifetime maintenance costs of recent military systems often exceed their acquisition cost. And, since maintenance costs depend crucially on system

---

[1] Later sections discuss more fully what is meant by the "production process" and the implications of allowing it to change.

characteristics which reflect early design decisions, maintenance cost implications need to be considered early in the acquisition process. This framework includes the system characteristics which drive maintenance costs. It assumes that several system characteristics determined within the model framework can selectively reduce maintenance costs, while other variables affecting maintenance costs--such as operating hours per month--remain outside the scope of the model.

The purpose of any military system is to provide operational effectiveness and this is the last activity encompassed by the model framework. Operational effectiveness constitutes the output of the acquisition process. All the other activities and their associated expenditures contribute to producing the achieved level of operational effectiveness. Aggregate effectiveness depends on the performance characteristics of individual systems, the proportion of the time each system is operationally available, and the quantity of systems. Following sections explain how these components of the effectiveness measure depend on early decisions in the acquisition process and discuss acquisition activities in more detail.

B. THE GENERAL LIFE CYCLE MODEL OF PROCESSES AND RELATIONSHIPS

Initial Development Phase

The initial development phase extends from program initiation until initial production begins. It consists of efforts which this framework divides into four categories: (1) efforts to achieve system performance, (2) efforts to achieve system availability, (3) efforts to minimize system production costs, and (4) testing.

The model permits an analyst to explore program outcomes as a function of different expenditure levels among the four categories. The first three categories capture basic system characteristics--performance, availability, and cost. The fourth--testing--allows the model to include possible ways testing may reduce development efforts required in the other categories. A major research problem

is the extent to which development costs can be identified by category.[1]

For initial purposes, the model employs simplified metrics to indicate system characteristics. The performance metric consists of a composite of multiple characteristics--such as range, speed, and payload--which determine a system's ability to perform a particular mission.[2] The availability metric indicates the probability that a system is available for a mission. The availability metric embodies both reliability--how long a system will perform without failure--and maintainability--the amount of time required to repair failures. Finally, the production cost metric provides an indication of how costly it is to produce a system. It depends on the extent of exotic, expensive materials required in the system, the extent of unusual components required, the degree of standardization, and other factors.

The preliminary representation of initial development assumes that development expenditures uniquely determine system characteristics, without uncertainties. Under these conditions the model divides initial development expenditures into these categories:

DC_{11} ≡ initial development expenditures on performance
DC_{12} ≡ initial development expenditures on availability
DC_{13} ≡ initial development expenditures on producibility
DC_{14} ≡ initial development test expenditures.

And, the model relates initial values of performance and availability metrics to development expenditures thus:

---

[1]Previous unpublished Rand research suggests that, at least with spacecraft reliability characteristics, this problem may be partially manageable.

[2]In this study I do not attempt to derive the scalar measure of performance and have no direct need for it. A compehensive application of the model would require the development of such a metric.

$P_o \equiv$ scalar metric of initial system performance

$$P_o = P_o(DC_{11}, DC_{14}) \tag{1}$$

$A_o \equiv$ scalar metric of initial system availability

$$A_o = A_o(DC_{12}, DC_{14}, P_o) \tag{2}$$

These relationships treat the development costs, DC_{1j}, as decision variables. Selecting a set of development expenditures results in the attainment of specific initial system characteristics. Relationships (1) and (2) suggest that both test expenditures and direct expenditures on each characteristic determine the level achieved. Further, relationship (2) reflects the probable situation that the performance level influences system availability. Since increases in development expenditures would be desirable only if they produced increases in performance and availability, we expect

$$\frac{\partial A_o}{\partial(DC_{12})}, \frac{\partial P_o}{\partial(DC_{11})} > 0.$$

Intuitively, we would expect increases in performance and availability to become more costly as their levels increase, or

$$\frac{\partial^2 A_o}{\partial(DC_{12})^2}, \frac{\partial^2 P_o}{\partial(DC_{11})^2} < 0.$$

These functions would probably behave similarly with respect to expenditures on testing, or

$$\frac{\partial A_o}{\partial(DC_{14})}, \frac{\partial P_o}{\partial(DC_{14})} > 0,$$

and

$$\frac{\partial^2 A_o}{\partial (DC_{14})^2}, \frac{\partial^2 P_o}{\partial (DC_{14})^2} < 0.$$

Finally, empirical observations suggest that high performance systems often suffer from reliability problems, or a tradeoff between performance and availability occurs such that

$$\frac{\partial A_o}{\partial P_o} < 0.$$

A more complete model of the initial development process could include the uncertainties associated with trying to obtain given performance and availability values. For example, relationship (1) might be a predictive equation for P_o with an uncertainty or error term. The uncertainty might be a function of the expected value of P_o and the expenditures, DC_{11} and DC_{14}. This complication deserves further examination, but goes beyond the scope of this initial analysis. In its present form, the model assumes the developer knows precisely what the initial characteristics, P_o and A_o, will be. It then allows him the option of achieving the desired final characteristics in two steps, as described later.

Initial Production Phase

Initial production begins at the end of initial development. The system characteristics, development expenditures on producibility, production rate, and quantity of items produced determine initial production costs.

The model separates production costs into fixed and variable costs. The former component captures costs that reflect the scale of the production process and are not variable in the short run. Variable costs, on the other hand, vary directly with production rate changes.

For purposes of this study, the approach assumes the contractor selects a production process based on a specified target production

rate, r_s, and is not free to change the process later.[1] The approach assumes the annual production total cost curve is selected from a family of curves relating total cost to production rate, with all other variables fixed, as shown in Fig. 5.[2] Given r_s, the producer selects plant size, S^o, to minimize total cost. In the example shown in Fig. 5, the minimum total cost at $r = r_s$ is TC^o and optimum plant size is $S^o = S_3$. Notice that if production occurs at a lower rate, such as r_a, a smaller plant size, S_2, would have been a less costly choice.

System production cost depends on the characteristics of the system produced. This framework assumes the initial performance and availability characteristics, P_o and A_o, embody all system factors that influence production costs. And, the amount spent during initial development on producibility, DC_{13}, directly affects production costs.

Letting VC be variable production costs per unit time, and S^o be fixed production costs per unit time, we can write

$$PC_1 \equiv \text{initial production phase cost}$$

$$PC_1 = [S^o + VC(S^o, DC_{13}, P_o, A_o, r_1)] \cdot Q_1/r_1 \qquad (3)$$

or,

$$PC_1 = PC_1(S^o, DC_{13}, P_o, A_o, r_1, Q_1). \qquad (4)$$

In expression (3) the fixed and variable costs apply per unit time, so they must be multiplied by the length of the production phase. With Q_1 equal to the quantity produced during initial production and

---

[1] This may not be too far from typical military programs when production lines operate significantly below capacity. Following the model through with this assumption allows us to assess its consequences.

[2] The shape of the total cost curves reflects conventional economics theory as presented in texts such as: Walter Nicholson, *Microeconomic Theory*, Dryden Press, Illinois, 1972.

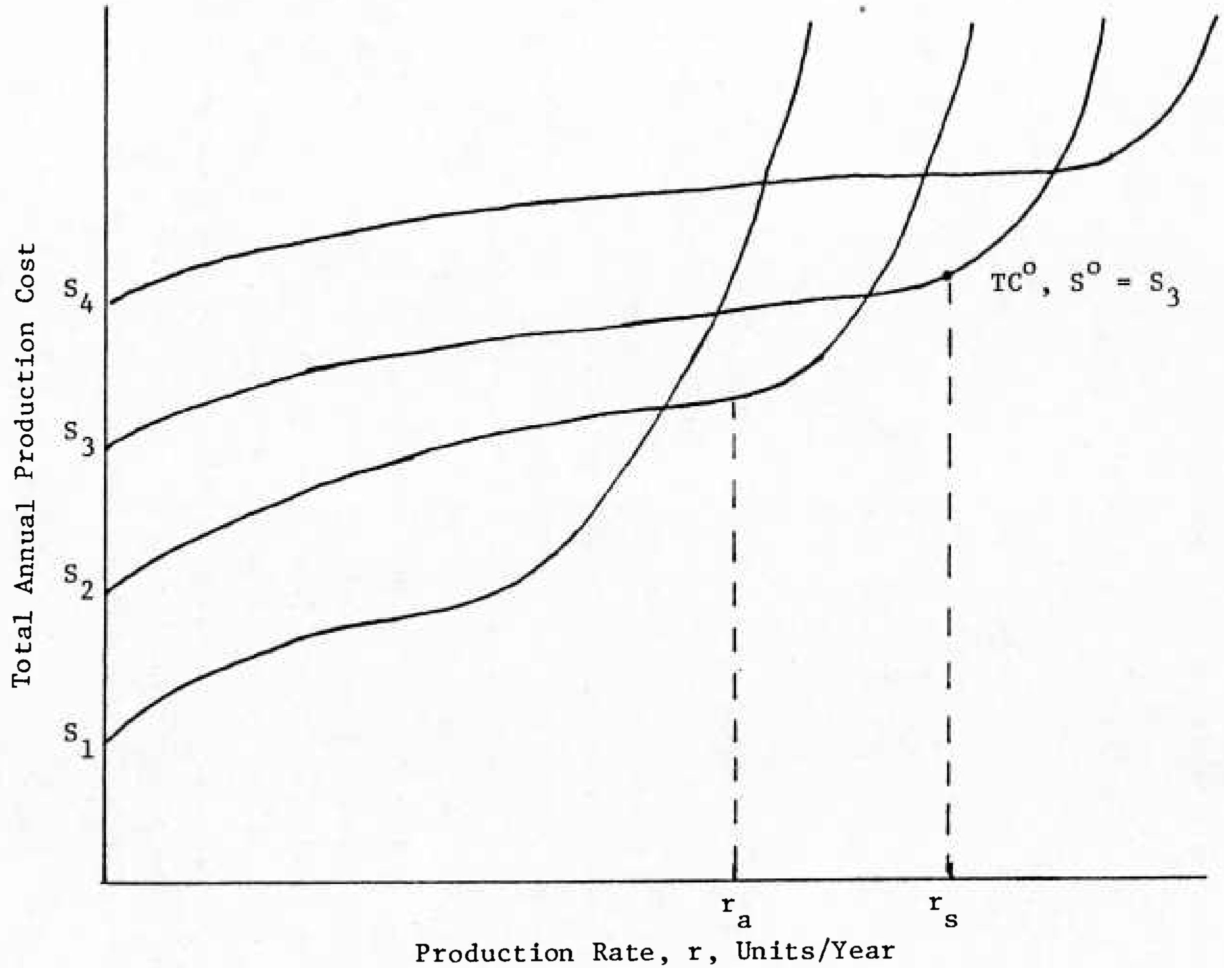


Fig. 5—Annual total production cost versus production rate for varying fixed costs

As production rate increases, the production-cost curve that minimizes costs has higher fixed costs.

r_1 defined as the initial annual production rate, the length of this production phase equals the ratio, Q_1/r_1.

Production costs would probably depend on two of the decision variables as shown below.

$$\frac{\partial(PC_1)}{\partial(DC_{13})} < 0$$

$$\frac{\partial(PC_1)}{\partial Q_1} > 0.$$

The first inequality reflects arguments developed earlier for P_o and A_o. The second inequality just indicates that total production costs increase with the production quantity. In addition to these relationships, PC_1 probably increases with higher performance levels, P_o. P_o, however, does not represent a basic decision variable since it depends directly on the development expenditures. No clear relationships exist between the other variables and PC_1. Certain approaches for increasing A_o, such as using component redundancy, would likely increase production costs; others, such as component standardization, might decrease production costs. The curves in Fig. 5 show that the derivative of annual production costs with respect to production rate would be positive. However, total production costs, as in (3), have an additional dependence on the inverse of production rate. Therefore, the sign of the derivative probably would vary for different values of r_1.

Follow-On Development Phase

The follow-on development phase occupies the same time span as the initial production phase. This occurs because follow-on development, in this framework, provides information on what system modifications are required and leads to their development. When follow-on development is completed, all necessary modifications become available; then the initial production phase ends, and full-scale production and modifications begin.

The model also allows for operating experience to partially substitute for follow-on development. As systems accrue operating experience during the initial production phase, the operating data may reveal necessary modifications. This operating experience may reduce the need for other development activities to identify necessary modifications, and thus reduce the necessary scope of follow-on development.

This model assumes follow-on development expenditures depend principally on the extent of required modifications. With the desired final performance level denoted by P_f, and the desired final availability level by A_f, the required incremental changes in these characteristics can be defined as follows:

$$\Delta P \equiv P_f - P_o$$

$$\Delta A \equiv A_f - A_o.$$

These desired changes in the characteristics must be achieved through modifications developed through the follow-on development process. Thus, the required follow-on development expenditures should depend on the quantities ΔP and ΔA.

As noted above, operating experience during this phase could reduce the extent of follow-on development effort required. The magnitude of operating experience acquired depends on the quantity of systems available, Q_1, the time period involved, and the operating rate. Since, in this model, the time period equals the quantity production divided by the production rate, r_1, the model can include production rate and eliminate time. If the operating rate, OH_1, equals the proportion of time systems operate to produce operating data, then the following relationship can be written:

$$DC_2 \equiv \text{follow-on development cost}$$

$$DC_2 = DC_2(\Delta P, \Delta A, r_1, Q_1, OH_1). \qquad (5)$$

The length of this phase has two possible further effects on the costs. If this phase is compressed substantially, costs might rise because of inefficient use of inputs. For example, it might require 100 engineers to do the same development work in one month that 20 could do in four months. On the other hand, if development extends over a very long time period, other cost penalties might result. For example, cumulative overhead costs might dominate other costs. Since time has already been included implicitly through Q_1 and r_1, the relationship need not include it explicitly. One simply needs to be aware that it enters this relationship in several ways.

In light of the above observations, the following relationships probably hold:

$$\frac{\partial(DC_2)}{\partial(\Delta P)}, \frac{\partial(DC_2)}{\partial(\Delta A)} > 0$$

$$\frac{\partial(DC_2)}{\partial(OH_1)} < 0.$$

Positive values of ΔP and ΔA, i.e., improvements in the characteristics of P_o and A_o, would surely require increased development expenditures, and this situation seems most probable. If degradations of the characteristics were desired, development expenditures might either decrease or increase; but, decreasing the performance and availability seems unlikely. Thus, the positive partial derivatives, with both ΔP and ΔA positive, seem most probable. Under the framework conditions in which operating experience could replace some development expenditures, an increase in OH_1 would decrease development expenditures. Since r_1 and Q_1 enter the relationship in several ways, however, we can make no inference about how changes in their values might affect DC_2.

Full-Scale Production Phase

Full-scale production begins at the end of initial-phase production. Typically, production rate would increase and would remain at a high level through the end of full-scale production.

Consistent with earlier distinctions between production and modification activities and costs, the model assumes that full-scale production costs capture only the costs of continuing production of the *initial* system design. It also assumes the basic production process remains the same, as does the basic production cost function. However, the framework allows scaling up the process to achieve higher production rates.

Because of the similarities between the two production phases, the relationship for full-scale production costs parallels that for initial-phase production costs. The dependence on the initial system characteristics remains, but the production rate and quantity are replaced by their full-scale production phase values, r_2 and Q_2. Thus, we have:

$$PC_2 \equiv \text{full-scale production phase costs}$$

$$PC_2 = PC_2(S^o, DC_{13}, P_o, A_o, r_2, Q_2).\text{[1]} \tag{6}$$

The derivatives should behave like those for Eq. (4). Thus, the following relationships should hold:

$$\frac{\partial(PC_2)}{\partial(DC_{13})} < 0$$

$$\frac{\partial(PC_2)}{\partial P_o} > 0.$$

$$\frac{\partial(PC_2)}{\partial Q_2} > 0.$$

As before, the signs of the other derivatives remain indeterminate.

---

[1]Note that this relationship assumes the same production process occurs as in the initial production phase. In a real program, planners might have the freedom to vary some characteristics, such as S^o. We noted earlier, however, that actual programs do not appear to plan extensively for two different production phases.

Modification Process

In this framework, the modification process occurs concurrently with the full-scale production phase. The model assumes all necessary modifications are identified and developed during the follow-on development phase, and implementation of the modifications occurs only during full-scale production.[1]

In this model the modification process covers all changes made to the initial design. As pointed out earlier, modification costs in military programs often lose their identity when they become part of production cost growth. The definition here prohibits this by distinguishing between the production costs of the original design and the costs associated with subsequent design changes. The modification cost category includes all of the latter costs.

Modifications occur either through retrofit or on the production line. The complete set of modifications brings all systems to the desired performance and availability levels, P_f and A_f. Systems produced during the initial production phase require modifications implemented through retrofit activities. Systems produced during the full-scale production phase require production-line modifications. These two processes may differ significantly in material and labor required and, as a result, costs per modified system.

The magnitude of modification costs depends, therefore, on the extent of changes required, ΔP and ΔA, and the quantities of systems produced during the two production phases, Q_1 and Q_2. The framework leads to the following relationship:

$$M \equiv \text{modification costs for all systems produced}$$

$$M = M(\Delta P, \Delta A, Q_1, Q_2). \tag{7}$$

---

[1]This simplifies the real-world situation in which modifications may be developed during full-scale production and continue to be implemented after termination of production. This simplification here not only makes the problem more manageable, but also focuses the analysis on those modifications most likely to be affected by changes in acquisition strategy.

Since modification costs would probably increase with the magnitude of modifications required, we would expect

$$\frac{\partial M}{\partial(\Delta P)}, \frac{\partial M}{\partial(\Delta A)} > 0.$$

The same argument regarding the signs of the derivatives of DC_2 applies here: Though modifications intended to degrade system characteristics would possibly cause M to increase, such modifications are untypical of actual programs.[1] Since empirical evidence suggests retrofit costs usually exceed comparable production-line modification costs, we can make an observation about the effects of Q_1 and Q_2 on modification costs. If the total quantity of items must equal a constant, then we expect:

$$\frac{\partial M}{\partial Q_1} > 0, \frac{\partial M}{\partial Q_2} < 0 \qquad \text{with both } Q_1 \text{ and } Q_2 \text{ varying but } Q_1 + Q_2 = \text{constant.}$$

Maintenance Activity

The last cost category in this framework consists of maintenance costs. Maintenance activities require sizable annual outlays over a system lifetime to pay for maintenance labor and parts.

Aggregate lifetime maintenance costs depend on the quantity of systems, failure frequency, cost per repair, operating rate, and system lifetime. The total quantity of systems equals the sum of the number of systems produced during the initial and full-scale production phases. The final availability of the system, A_f, reflects its failure frequency. Costs per repair depend on system sophistication and complexity, which are functions of system performance, P_f. The operating rate indicates how much time a system spends in an operating condition and, for our purposes, this rate, OH_2, is determined exogenously. Finally, total maintenance costs depend on the system service lifetime, L. Though this parameter may reflect intrinsic system

---

[1] We could probably just replace ΔP and ΔA with $|\Delta P|$ and $|\Delta A|$ in both (5) and (7) and make these relationships unequivocally true.

characteristics, the model treats it as an exogenous variable.

Maintenance cost can then be expressed as follows:

$$\text{MAINT} \equiv \text{fleet lifetime maintenance costs}$$
$$\text{MAINT} = \text{MAINT}(Q_1 + Q_2, A_f, P_f, OH_2, L). \quad (8)$$

This relationship relies on the assumption that, after modifications, all systems have identical design features and characteristics.[1]

The signs of the cost function derivatives with respect to the variables are relatively obvious and unambiguous, as follows:

$$\frac{\partial(\text{MAINT})}{\partial Q_1}, \frac{\partial(\text{MAINT})}{\partial Q_2} > 0 \qquad \text{if } Q_1, Q_2 \text{ vary independently}$$

$$\frac{\partial(\text{MAINT})}{\partial A_f} < 0$$

$$\frac{\partial(\text{MAINT})}{\partial P_f} > 0.$$

The derivatives with respect to OH_2 and L would be positive but, since these are exogenously determined in this model, they are not included here.

Effectiveness

The output of an acquisition program consists of a quantity of systems with specific capabilities, or, in other words, an aggregate effectiveness level. In this context, effectiveness depends on the quantity of systems which (1) are available, (2) operate without failure, and (3) successfully meet the needs of a given mission. This output measure most obviously applies to military systems, but serves as well for systems as diverse as buses or television sets.

[1]This may not always be true in an actual program but it is usually the desired objective. This assumption makes this cost function more tractable for analysis.

The variables which define the effectiveness level have all been presented before. The relationship below follows from the above description.

$$E \equiv \text{aggregate level of effectiveness}$$

$$E = E(Q_1 + Q_2, P_f, A_f). \tag{9}$$

With the definitions of P_f and A_f presented earlier, increases in all of the variables should produce increased effectiveness. Therefore, the following relationships should hold:

$$\frac{\partial E}{\partial Q_1}, \frac{\partial E}{\partial Q_2} > 0$$

$$\frac{\partial E}{\partial P_f} > 0$$

$$\frac{\partial E}{\partial A_f} > 0.$$

Table 2 presents a complete summary of the variables and relationships that constitute the general life cycle model developed here.

C. A NARROWED MODEL FOR APPLICATION TO PAS

Introduction

The problem described here involves the modification costs, in military programs, required to improve system characteristics from their initial values to the desired final values. Modifications of some military systems, especially in the late 1960s, have achieved considerable notoriety because of the very costly and extensive changes involved. Often, the cost of modifications to correct certain deficiencies and obtain a desired performance or availability level has been so large that the modifications were simply postponed indefinitely. As a result, system performance or availability never improved and, as

Table 2

SUMMARY OF GENERAL MODEL

	Symbol	Definition	Functional Relation
Decision Variables	DC_{11}	Initial development expenditure on performance	None
	DC_{12}	Initial development expenditure on availability	None
	DC_{13}	Initial development expenditure on producibility	None
	DC_{14}	Initial development test expenditures	None
	A_f	Final availability level	None
	P_f	Final performance level	None
	r_1	Initial production rate	None
	r_2	Full-scale production rate	None
	Q_1	Initial production quantity	None
	Q_2	Full-scale production quantity	None
	OH_1	Initial operating rate	None
	S^o	Fixed production costs, annualized	None
Other Variables	P_o	Initial performance level	$P_o(DC_{11},DC_{14})$
	A_o	Initial availability level	$A_o(DC_{12},DC_{14},P_o)$
	ΔP	Incremental change in performance level	$\Delta P = P_f - P_o$
	ΔA	Incremental change in availability level	$\Delta A = A_f - A_o$
	OH_2	Full-scale operating rate	Given exogenously
	L	System lifetime	Given exogenously
Cost Functions	PC_1	Initial production phase costs	$PC_1(S^o,DC_{13},P_o,A_o,r_1,Q_1)$
	DC_2	Follow-on development costs, including initial operating costs	$DC_2(\Delta P,\Delta A,r_1,Q_1,OH_1)$
	PC_2	Full-scale production costs	$PC2(S^o,DC13,P_o,A_o,r2,Q2)$
	M	Modification costs for all systems produced	$M(\Delta P,\Delta A,Q_1,Q_2)$
	MAINT	Fleet lifetime maintenance costs	$MAINT(Q_1 + Q_2,A_f,P_f,OH_2,L)$
Effective-ness	E	Aggregate level of effectiveness	$E(Q_1 + Q_2,P_f,A_f)$

suggested by Eq. (9), effectiveness fell short of the desired level. Therefore, the discrepancies between initial system characteristics and the desired, final characteristics have resulted in one or more types of significant costs.

Previous research has developed several recommendations that respond to these problems associated with system deficiencies. Many of them have been combined in the proposed Phased Acquisition Strategy discussed earlier. A PAS program, during the development phase, would emphasize the life cycle impacts of development decisions and activities. It would explicitly incorporate a low-rate initial production phase to allow problem identification and correction before large quantities of systems had been produced. And, it would utilize early test and flight experience data to reassess the effects of system characteristics on support cost and effectiveness levels.

The Problem

The research proposed here addresses a particular problem framed within the acquisition framework developed earlier: *Given a specific system design at the end of initial development and a set of required design modifications, how can the transition from development to production be structured to accomplish these modifications at minimum life cycle costs for a given effectiveness level?*

This problem does not encompass the initial development phase; thus, it does not address possible changes in the allocation of development expenditures and implications for subsequent acquisition decisions and outcomes. This exclusion implies DC_{11}, DC_{12}, DC_{13}, and DC_{14} are given. Likewise, it implies the initial system characteristics, P_o and A_o, are given. Since the set of modifications is given, the changes in system characteristics, ΔP and ΔA, and their final values, P_f and A_f, are fixed, as well. Since the problem definition specifies the aggregate effectiveness level, and P_f and A_f are fixed, the total quantity of systems, $Q_1 + Q_2$, is also fixed. Finally, the characteristics of the production process are assumed to be given,

thus fixing the production cost functions, PC_1 and PC_2, and the fixed cost, S^o.[1]

Under these conditions the number of decision variables reduces to five: r_1, Q_1, r_2, Q_2, and OH_1. The first two, initial production rate and quantity, determine the scope of the initial production phase. The second pair, full-scale production rate and quantity, determine the scope of the full-scale production phase. The last variable, flight rate during follow-on development, determines, along with r_1 and Q_1, the extent of the flight program during initial production. The two quantities, Q_1 and Q_2, determine the distribution of modification expenditures between retrofit and production-line changes.

Specific Cost Functions

The specific cost functions used below satisfy three principal requirements: (1) they are compatible with intuitive expectations, (2) they do not violate empirical observations, and (3) they allow tractable solutions of the problem. Though these cost functions could be developed further, they serve our present needs satisfactorily.

First, consider the production cost function. Conventional economics theory suggests that, as a function of quantity-produced-per-unit-time, total costs would behave as shown by the family of curves in Fig. 5. When a production line is open, fixed costs are incurred independent of production quantity even when no items are produced. At low production rates, marginal costs are high, but decreasing. At intermediate production rates, marginal costs level out and reach a minimum. At high production rates, marginal costs increase sharply. Average costs follow a similar pattern but the minimum cost point shifts toward a higher production level and the marginal cost curve intersects the average cost curve at its

---

[1] Carrying through this assumption permits a first analysis and evaluation of this specific problem. The results highlight the effects of this assumption and allow us to evaluate its significance.

minimum.[1] This analysis uses a cost function quadratic in production rate to approximate this behavior. This function produces the expected behavior for average cost but not marginal cost, which increases linearly over the entire production range. Figure 6a shows a quadratic cost function and Fig. 6b shows the corresponding marginal and average cost curves. Though this cost-function specification does not give the exact behavior expected, it does suffice at all but the lowest production levels.[2]

Using the year as the time unit, we can write the annual production cost function as:

$$PC = \alpha_1 + \alpha_2 \cdot r + \alpha_3 \cdot r^2$$

where r equals the annual production quantity and PC equals annual production cost.[3] Since this function gives costs per year, it must be multiplied by the length of the production phase to determine total production-phase costs. Thus, for the two production phases, we have

$$PC_1 = (\alpha_1 + \alpha_2 \cdot r_1 + \alpha_3 \cdot r_1^2) \cdot Q_1/r_1 \tag{10}$$

$$PC_2 = (\alpha_1 + \alpha_2 \cdot r_2 + \alpha_3 \cdot r_2^2) \cdot Q_2/r_2 \tag{11}$$

---

[1]This behavior holds with U-shaped cost curves because (1) to the left of the minimum, average cost exceeds marginal cost so producing one more unit reduces average cost; (2) to the right of the minimum, marginal cost exceeds average cost so additional production increases average cost; and (3) at the minimum cost point, marginal cost equals average cost.

[2]A cubic function would produce the entire behavior expected, but this function was rejected because of analytic complexities it introduced in the solution procedure.

[3]Note that all coefficients introduced in this and later cost functions will be positive by convention.

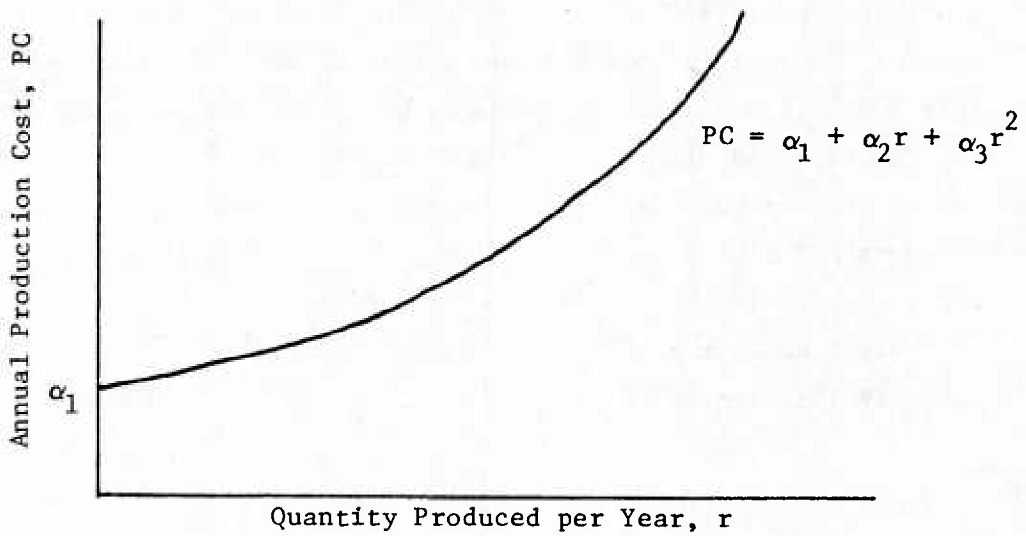


Fig. 6a—Quadratic annual production cost function

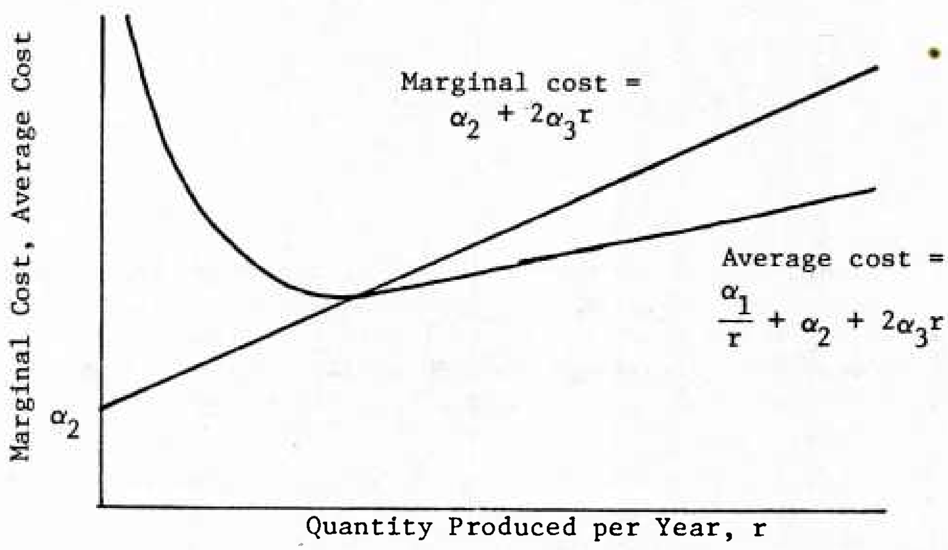


Fig. 6b—Annual marginal, average costs for quadratic annual production cost function

Notice that these functions have identical structures and coefficients consistent with the earlier assumption that the same production process applies during both production phases.[1]

The second cost function applies to the follow-on development phase. These costs depend on the extent of modifications required, but in this problem the modifications have been given exogenously. The earlier discussion suggests that follow-on development costs increase for both very short and very long follow-on development phases, and decrease with operating experience. During this phase the quantity of items produced, $Q(t)$, is a linear function of time, or

$$Q(t) = r_1 \cdot t.$$

If OH_1 is defined as the proportion of time each system operates exclusively to generate operating-experience data, and t_{P1} is the length of the production phase, then the extra operating hours, XOH, can be calculated thus:

$$XOH = \int_0^{t_{P1}} Q(t) \cdot OH_1 \cdot dt$$

$$= \int_0^{Q_1} \frac{Q(t) \cdot OH_1 \cdot dQ}{r_1}$$

$$= \frac{Q_1^{\ 2} \cdot OH_1}{2 \cdot r_1}$$

From these results and the previous conditions, we postulate the following cost function for follow-on development:

---

[1]Note that the proposed production-cost function does not include the conventional learning-curve effects; however, an exploration of this issue revealed that if learning carried over from one production phase to the other, the optimizing conditions would remain the same.

$$DC_2 = \alpha_4 \cdot \frac{r_1}{Q_1} - \alpha_5 \cdot \frac{Q_1^{\,2} \cdot OH_1}{2 \cdot r_1} + \alpha_6 \cdot \frac{Q_1}{r_1} \; . \tag{12}$$

The first term captures the cost increase caused by compressing the development program, and the third term captures cost increases due to stretching out the program. The coefficient, α_5, indicates how many dollars the development program costs decrease for each additional operating hour.

This framework specification should also include the costs incurred because of the operating program during follow-on development. If costs per operating hour equal OC_1, then the operating costs associated with acquiring additional operating experience, the extra operating costs, are simply

$$XOC_1 = \frac{OC_1 \cdot Q_1^{\,2} \cdot OH_1}{2 \cdot r_1} \; . \tag{13}$$

The modification cost function has a simple form in this case. Let the retrofit costs per system equal a constant, β_1, and the production-line modification costs per system, β_2, equal a different constant. Previous analyses lead us to expect that β_1 exceeds β_2 significantly. Thus, modification costs are simply

$$M = \beta_1 \cdot Q_1 + \beta_2 \cdot Q_2 . \tag{14}$$

Maintenance costs, as described in Eq. (8), depend on the total quantity of systems, $Q_1 + Q_2$, and variables determined outside the bounds of this problem. Since the total quantity of systems does not change in this problem, no variation occurs in maintenance costs. Therefore, the maintenance cost component does not affect the optimization in this analysis problem.[1]

---

[1]Note that a more general problem might allow tradeoffs between P_f and A_f which might, in turn, have significant effects on maintenance cost.

Finally, by similar reasoning, the effectiveness constraint has no effect on the problem. P_f and A_f have been determined exogenously and the total quantity of systems does not vary; therefore, the aggregate effectiveness level is necessarily achieved.

The problem then becomes that of minimizing the relevant life cycle cost consisting of the cost components identified above. Thus, life cycle cost is

$$LCC = PC_1 + PC_2 + DC_2 + XOC_1 + M$$

and the problem requires choosing the variables r_1, Q_1, r_2, Q_2, and OH_1 to minimize LCC.

Table 3 summarizes the decision variables, parameters, and cost functions in the narrowed model.

The Solution

The solution technique involves setting the first order derivatives of the function LCC equal to zero and satisfying several second order conditions. First, two observations simplify the problem. Since Q_1 and Q_2 are related through a side condition requiring that their sum be constant, one solution approach could use a Lagrangian multiplier technique. However, for this problem it is simpler to eliminate one of the quantities, say Q_2, everywhere it appears by substituting its definition in terms of the other, Q_1. Thus, with the total quantity equal to Q_T, we substitute for Q_2 everywhere using

$$Q_2 = Q_T - Q_1$$

Also, OH_1 is one of the decision variables, but since it equals a proportion, its value ranges from zero to one. Instead of attempting to solve the problem by introducing an inequality constraint on OH_1, we can solve the problem using the other variables and then treat OH_1 as a parameter.

Table 3

SUMMARY OF NARROWED MODEL

	Symbol	Definition	Functional Relation
Decision Variables	r_1	Initial production rate	None
	r_2	Full-scale production rate	None
	Q_1	Initial production quantity	None
	OH_1	Initial operating rate	None
Other Variables	Q_2	Full-scale production quantity	$Q_2 \equiv (Q_1 + Q_2) - Q_1$
	$Q_1 + Q_2$	Total production quantity	Given exogenously
	OC_2	Initial operating costs	Given exogenously
Parameters	α_1	Annualized fixed production costs	Sensitivity variable
	α_2	Production cost dependence on production rate	Sensitivity variable
	α_3	Production cost dependence on production rate squared	Sensitivity variable
	α_4	Follow-on development cost dependence on schedule compression	Sensitivity variable
	α_5	Follow-on development cost decrease per hour of operating time	Sensitivity variable
	α_6	Annualized fixed follow-on development costs	Sensitivity variable
	β_1	Retrofit modification cost per unit	Sensitivity variable
	β_2	Production-line modification cost per unit	Sensitivity variable
Cost Functions	PC_1	Initial production phase costs	$PC_1 = (\alpha_1 + \alpha_2 r_1 + \alpha_3 r_1^2) \cdot Q_1/r_1$
	PC_2	Full-scale production costs	$PC_2 = (\alpha_1 + \alpha_2 r_2 + \alpha_3 r_2^2) \cdot Q_2/r_2$
	DC_2	Follow-on development costs	$DC_2 = \alpha_4 \cdot \frac{r_1}{Q_1} - \frac{\alpha_5 \cdot Q_1^2 \cdot OH_1}{2r_1} + \alpha_6 \cdot \frac{Q_1}{r_1}$
	XOC_1	Extra operating costs	$XOC_1 = \frac{OC_1 \cdot Q_1^2 \cdot OH_1}{2r_1}$
	M	Modification costs	$M = \beta_1 Q_1 + \beta_2 Q_2$
Effectiveness	E	Aggregate level of effectiveness	Given exogenously

Thus, the problem reduces to one involving three independent variables: r_1, r_2, and Q_1. Appendix A presents the approach used to solve this problem. This approach provides an explicit solution for r_2, and two equations in r_1 and Q_1.

IV. APPLICATION OF THE NARROWED MODEL TO THE EARLY PRODUCTION PHASE

A. CHARACTERISTICS OF THE MODEL

This section presents the details of an application of the model developed in the previous chapter. The following four characteristics describe the model:

- o structure
- o inputs
- o optimization technique, and
- o outputs.

Structurally, the model frames the acquisition process in a manner to optimize program cost-effectiveness. It consists of a set of cost functions capturing the key activities in the narrowed model. The cost functions originate in economics theory, from empirical research, or from empirically based observations. The structure treats the components of effectiveness--system technical performance, system availability, and system quantity--as given and constant.

The model requires the characteristics of the cost functions as inputs. Specifically, it uses features, such as fixed production costs, retrofit costs, and operating costs, as inputs to define individual programs.

The optimization technique simply minimizes costs for the given effectiveness level. Since effectiveness remains constant, only the variables which determine costs affect the optimization. Given the proposed cost functions, this process entails setting several first order derivatives equal to zero and satisfying necessary second-order conditions.

Finally, this technique leads to the set of optimum decision variables. These variables provide the minimum cost solution under the conditions defined by the input program cost characteristics. These optimum decision variables constitute the outputs of the model.

B. DEVELOPING A BASE CASE ACQUISITION PROGRAM

Solving for the initial production rate r_1 and production quantity Q_1 requires an iterative approach best done with a computer program.[1] I have developed a computer program to solve for r_1, r_2, and Q_1 given specific values of the coefficients α_1, α_2, α_3, etc. Using the program requires initial judgments about reasonable values of the coefficients based on characteristics of a hypothetical acquisition program. Given initial coefficient values, sensitivity analyses then provide information about the sensitivity of the results to values of the coefficients.

This preliminary analysis uses a hypothetical aircraft acquisition program as the base case. The key characteristics of the program are:

- o average production cost is about $10 million,
- o total quantity produced is 300 aircraft,
- o optimum full-scale production rate is 100 aircraft per year,
- o initial-phase production lasts about one year, and
- o modifications costs per aircraft are about 5 percent of average unit production costs.[2]

These characteristics and additional assumptions, as described in Appendix B, lead to the base case values of the cost parameters shown in Table 4.

---

[1] See Eqs. (22) and (23) in Appendix A.

[2] These values do not represent any specific aircraft program but, rather, constitute reasonable values that fall within a range covered by recent programs. Production costs of the F-111A averaged about $8.2 million in then-year dollars. Total production quantities have varied from 81 C-5As to a planned buy of 729 F-15s. The F-111 and F-15 production rates peaked at about 100 to 120 aircraft per year. Though most programs do not have a low-rate production phase, as defined here, a program such as the F-15 required about one year to transition from the very low production rate during development to full-scale production. And, most estimates of modification costs equal about 5 to 10 percent of production costs.

Table 4

BASE CASE PARAMETER VALUE

Parameter	Definition	Value
α_1	Annualized fixed production costs	$\$3 \cdot 10^8$/yr
α_2	Production cost dependence on production rate	$\$4 \cdot 10^6$/(aircraft/yr)/yr
α_3	Production cost dependence on production rate squared	$\$3 \cdot 10^4$/(aircraft/yr)^2/yr
α_4	Follow-on development cost dependence on schedule compression	$\$5 \cdot 10^6$/yr
α_5	Follow-on development cost decrease per hour of operating time	$\$2 \cdot 10^3$/hr
α_6	Annualized fixed follow-on development costs	$\$5 \cdot 10^7$/yr
β_1	Retrofit modification cost per unit	$\$7.5 \cdot 10^5$/aircraft
β_2	Production-line modification cost per unit	$\$2.5 \cdot 10^5$/aircraft

Under these conditions the computer program solves the necessary relationships for r_1, r_2, and Q_1 to minimize costs. As specified in the assumptions, the optimum full-scale production rate equals 100 aircraft per year. The optimum initial production rate is slightly less, 92 aircraft per year.[1] The initial production quantity equals 21 aircraft; therefore, the initial production phase length equals 0.23 years, or about 2.8 months. The full-scale production phase produces 279 aircraft. Table 5 summarizes the resultant optimum program characteristics and costs.

---

[1] Quantities reported are rounded off to the nearest integer for aircraft produced and production rates.

Table 5

BASE CASE CHARACTERISTICS AND COSTS

	Primary Characteristics	Cost	% of Total Costs
Initial production	Production rate = 92 aircraft/yr.	$214 million	6.9
Follow-on development	Phase length = 0.23 yr.	$33 million	1.1
Extra operating cost		$0.2 million	∿0
Full-scale production	Production rate = 100 aircraft/yr.	$2,790 million	89.3
Modifications	Retrofit quantity = 21 aircraft, production-line quantity = 279 aircraft	$86 million	2.8
Total cost		$3,123 million	100

These results for the base case show the significance of the different cost components. Production costs dominate total costs; initial production and full-scale production constitute about 96 percent of total costs. Follow-on development costs contribute only about one percent of the total, while the extra operating costs during the phase contribute less than one-hundredth of a percent. Modification costs, the primary concern of this analysis, constitute about three percent of total costs, or $86 million.[1]

It is informative to examine how sensitive program costs are to deviations in the program characteristics from their optimum values. Since full-scale production costs dominate the results, variations in the full-scale production rate would have the most significant

---

[1]These results basically reflect the assumptions upon which this case is based. The rather small contribution of modification costs to total cost follows from their assumed magnitude of about 5 percent of production costs. Optimum program characteristics and cost distributions would differ significantly in programs, such as the C-5A, where modifications constitute much more than 5 percent of production costs.

effects on total cost. Initial production costs constitute the second largest segment of total costs and, therefore, variations in initial production rate also would affect total costs significantly, but to a lesser degree. Finally, the value of the initial-production quantity would affect costs, but with less predictability because initial-production quantity enters several cost functions in different ways. The following table shows how a 50 percent increase or 50 percent decrease, in each of the variables, affects total costs.

Table 6

EFFECT OF NON-OPTIMUM VARIABLE VALUES ON TOTAL COSTS

Variable Changed from Optimum Value	New Value (% Change)	Total Cost, $\$10^9$	Cost Increase, $\$10^6$ (%)
None	Base case	3.123	0 (0)
r_2	150 (+50)	3.259	136 (4.4)
r_2	50 (-50)	3.542	419 (13.4)
r_1	138 (+50)	3.133	10 (0.3
r_1	46 (-50)	3.159	36 (1.2)
Q_1	32 (+50)	3.123	0 (0)
Q_1	11 (-50)	3.127	4 (0.1)

Within the bounds of this hypothetical acquisition program, only non-optimum choices of the full-scale production rate affect total costs significantly. Costs vary least with variations in the initial production quantity, Q_1. The initial production rate variations considered here increase costs an intermediate amount. The structure of the model and the values selected for the coefficients in the cost functions determine which variables affect costs the most. The following subsection examines how the model structure and coefficient values affect strategy optimization.

Model Coefficients, Acquisition Program Characteristics, and Model Validity

Varying the coefficient values in the cost relationship permits comparing program optimizations in the model with intuitive expectations. Based on the nature of the cost relationships used in the framework, one could partially anticipate how program optimization would vary with changes in the coefficients. Then, running the computer program with different cost coefficients reveals the calculated effects on the optimization solution.

Production costs depend on three coefficients--α_1, α_2, and α_3. Equation (21) in Appendix A shows that production rate r_2 optimization depends on only α_1 and α_3, or

$$r_2 = \sqrt{\alpha_1/\alpha_3} .$$

This relationship shows that optimum production rate would increase as fixed production costs, α_1, increase and as dependence on the square of production rate, α_3, decreases.[1] In other words, as fixed production costs become larger, the optimum production rate increases so that production terminates more quickly.

The relationship for follow-on development costs contains three coefficients--α_4, α_5, and α_6. One, α_4, indicates how much development costs increase when the follow-on development schedule is compressed. In this model the follow-on development schedule length equals the ratio of the initial production quantity to the initial production rate, or,

$$t_1 = Q_1/r_1.$$

[1]Note that α_3 indicates the increase in marginal cost with production rate. If $\alpha_3 \rightarrow 0$, i.e., marginal costs equal a constant, then the optimum full-scale production rate approaches infinity. The optimum initial production rate and quantity, r_1 and Q_1, however, remain low. The optimum values of r_1 and Q_1 exhibit the same dependence on the remaining coefficients as they do in the case of increasing marginal costs.

As the schedule-compression cost penalty, α_4, increases one would expect the optimum value of t_1 to increase. However, this would not indicate how the primary variables Q_1 and r_1 vary individually. If the schedule-extension penalty, α_6, increases, one would anticipate the opposite effect, i.e., the schedule should shorten. Again, this would not indicate how optimum Q_1 or r_1 vary. Finally, variations in α_5, the coefficient which indicates how much follow-on development cost decreases for each hour of operating time, also affect the optimum solution. The factor (Q_1^2/r_1) appears in Eq. (12) multiplied by the coefficient α_5, and this factor can be rewritten as $(Q_1 \cdot t_1)$. From this expression it would appear that if α_5 increases, the product $(Q_1 \cdot t_1)$ could decrease to achieve the same level of costs.

Modification costs depend on the extent of retrofit and production-line changes. From Eq. (14) each item modified through retrofit requires β_1 dollars, and each one modified on the production line costs β_2 dollars. The cost differential for making modifications through retrofit rather than on the production line equals $(\beta_1 - \beta_2)$. One would anticipate that increasing this differential would reduce the optimum initial production quantity, Q_1, i.e., those items requiring retrofit.

The optimization model can show how the coefficient changes discussed above actually affect optimum program characteristics. Table 7 shows how varying each coefficient, from one-tenth to ten times its base-case value, affects the optimum r_1, r_2, and Q_1. The production cost coefficient variations have the most significant effect on program characteristics. As predicted above, a large increase in α_1/α_3 produces a significant increase in the optimum r_2. It also increases r_1 an even larger proportion, and increases Q_1 as well. Changing α_4 and α_6 affects the phase length, t_1, as predicted. Surprisingly, though, neither coefficient affects the production rates to any degree; they achieve their schedule effects by simply increasing or decreasing the quantity, Q_1, produced during initial production. Somewhat unexpectedly, the variable, α_5, which indicates development cost savings resulting from operating experience, has no measurable effect on optimum program characteristics. Finally, the modification

Table 7

SENSITIVITY OF OPTIMIZATION RESULTS TO MODEL COEFFICIENT VARIATIONS

		Base Case	Production Costs		Follow-On Development Costs						Modification Costs	
			α_1/α_3		α_4		α_6		$(\alpha_5 - OC_1)$[a]		$(\beta_1 - \beta_2)$	
	Coefficient Change		×10	÷10	×10	÷10	×10	÷10	×10	÷10	×10	÷10
Program Variable	Expected Effect		Production Rate Increases	Production Rate Decreases	t_1 Increases	t_1 Decreases	t_1 Decreases	t_1 Increases	$(Q_1 \cdot t_1)$ Decreases	$(Q_1 \cdot t_1)$ Increases	Q_1 Decreases	Q_1 Increases
r_1	---	92	305	23	92	91	90	92	92	92	17	100
r_2	---	100	316	32	100	100	100	100	100	100	100	100
Q_1	---	21	43	6	68	6	9	30	21	21	2	32
t_1[b]	---	0.2	0.1	0.3	0.7	0.1	0.1	0.3	0.2	0.2	0.1	0.3

[b] $t_1 \equiv Q_1/r_1$; t_1 is not a primary design parameter.

[a] The difference, $(\alpha_5 - OC_1)$, represents the net cost effect of accruing additional operating hours to complement follow-on development.

cost coefficients have a significant effect on program characteristics, consistent with above expectations. Increasing the difference between β_1 and β_2 by a factor of 10, while keeping $\beta_1 = 3 \cdot \beta_2$, reduces the initial production quantity significantly. The reduction occurs through a substantial initial-production rate reduction and a shortening of the initial-production phase. In summary, none of these results contradicts the expected behavior of the optimum program characteristics when the cost coefficients vary.

In terms of model validity, several observations apply. First, production costs dominate, as they would in most real-world programs. The optimum program characteristics vary most with changes in the production cost function coefficients, and this appears consistent with the overall importance of production cost. Production cost functions have been extensively studied and should be reasonably amenable to estimation. Second, follow-on development cost coefficients, α_4 and α_6, appear to affect production rates insignificantly, but do have significant effects on the schedule length and production quantity. The coefficient α_6 simply indicates development costs that depend directly on time, such as overhead; these costs should be fairly predictable in a given program. The coefficient α_4 indicates the cost effects of compressing the development schedule. Though this effect has been acknowledged frequently and explored in prior studies, its quantification presents difficulties.[1] Third, the minimal effect of variations in the coefficient α_5, though surprising, provides reassurances about the usefulness of the model. The coefficient α_5 represents the most speculative term in the cost functions in this model. The fact that the value of this coefficient, over two orders of magnitude, has virtually no effect on the optimum program characteristics relieves most concerns over the proper

---

[1] See, for example: Marschak et al., p. 255; Harman, Alvin, *Choice Among Strategies for System Acquisition*, The Rand Corporation, P-4794, March 1972; Zschau, p. 48.

value for an admittedly speculative coefficient.[1] Finally, the modification cost coefficients have very significant effects on program optimization. Since concerns about levels of modification costs stimulated this analysis, the behavior of the model reinforces and mirrors the initial concerns. And, since modification costs have been studied and are fairly well defined in many programs, only minimal uncertainties should enter into their estimates. For these reasons, one should have confidence in the validity and utility of this model for analyzing program optimizations where modifications costs figure prominently.

These observations of the behavior of the model under different conditions provide insights into the relationship between acquisition program characteristics and program optimization. This research has concentrated on the PAS approach, and the insights provided by the modeling process have produced information about what kind of programs would or would not benefit from employing PAS. The next subsection discusses this issue.

---

[1] Note that the coefficient α_5 would have complex effects on program optimization if all possible values were considered. Furthermore, α_5 always appeared with the operating cost, OC_1, and operating rate, OH_1, in the postulated cost functions. Consequently, we should consider variations in the composite coefficient $(\alpha_5 - OC_1) \cdot OH_1$. A preliminary exploration indicated that as this variable went negative, that is when operating costs exceeded development cost savings, the optimum initial production rate and quantity decreased. This happens because the initial operating phase generates net costs under these conditions. With this variable equal to zero, that is, no operating time during this phase, the results did not differ from the base case. And, with the development cost-saving coefficient α_5 increasing, both the optimum initial production rate and optimum initial production quantity increase. However, Eq. (22), in Appendix A, provides a limit to these increases since the numerator in this expression becomes negative and the square root, imaginary, as Q_1 increases. Furthermore, by the nature of Eq. (12), follow-on development costs could have values less than zero for large α_5. This would occur only as an artifact of the functional form and would not imply costs could really fall below zero if extensive operating occurred. In summary, these results indicate that operating rates should be as high as practicable, but optimum program characteristics would not depend significantly on α_5 or OH_1.

Program Features and PAS

For our purposes, PAS can be characterized in terms of three basic decision variables--r_1, Q_1, and r_2--and the initial operating rate, OH_1. For reasons described earlier, the analysis does not include OH_1 as a decision variable. It should have a value as high as possible within the constraints of the program.[1] In terms of the initial-production/follow-on development phase, PAS takes advantage of a low initial production rate, r_1, over a moderate time period, $t_1 = Q_1/r_1$, to acquire operating and test data, conduct development, and avoid extensive retrofit. Once this phase had been completed, production would move to a high production rate, r_2, until completion of the production run. Thus, a low r_1, modest Q_1, and high r_2 would characterize a PAS program.

Table 7 suggests what variations in the cost-function coefficients would lead to optimum r_1, Q_1, and r_2 values consistent with the structure of a PAS program. In the base case, the coefficients result in an optimum program design with high r_1, modest Q_1, and high r_2. The coefficients α_1 and α_3, in the production cost function, totally determine r_2, since $r_2 = \sqrt{\alpha_1/\alpha_3}$.[2] Thus, in a PAS program, the relative values of α_1 and α_3 would have to be about the same as they are in the base case to achieve a high value for the optimum r_2. The earlier results also show that the optimum value of r_1 falls as the difference between retrofit and production-line modification costs, $(\beta_1 - \beta_2)$, increases. Thus, $(\beta_1 - \beta_2)$ would have to be higher than its base case value to favor a PAS program. Table 7 also shows that the length of the follow-on development phase, t_1, depends significantly on α_4 and α_6. Specifically, t_1 increases as α_4 increases and α_6 decreases. Thus, a suitable candidate program for PAS would have α_4 higher and α_6 lower than their base-case values. Finally, the earlier results show that optimum program design does not depend very

---

[1] See Eq. (21) in Appendix A.

[2] As noted before, OH_1 appears in combination with $(\alpha_5 - OC_1)$ and, in most circumstances, has little effect on the optimum program design. The PAS approach, however, emphasizes accumulating extensive early operating experience, thus encouraging large values of OH_1.

significantly on the value of α_5.[1] Thus, its value in the base case would probably suffice in a candidate PAS program. Table 8 summarizes the coefficient values, relative to their base-case values, that would favor a PAS approach.

Table 8

COST FUNCTION COEFFICIENT VALUES FAVORING PAS

	Coefficients				
Magnitude Relative to Base Case	α_1/α_3 Medium	α_4 High	α_6 Low	α_5 Minor Effect	$(\beta_1 - \beta_2)$ High

PAS Benefits and Their Dependence on Program Characteristics

The model described in this section has provided important information about the applicability of the Phased Acquisition Strategy and its potential benefits. The preceding discussion suggests that a program would benefit most from PAS when

- o large economic inefficiencies result from compressing the follow-on development and initial production phases,
- o only minimal cost penalties result from stretching-out follow-on development and initial production, and
- o modifications cost significantly more if implemented through retrofit rather than on the production line.

The first condition corresponds to high values of α_4, the second corresponds to low values of α_6; and, the third corresponds to large values of $(\beta_1 - \beta_2)$.

[1]Note that this is true only within what appears to be a reasonable range of values for the coefficient α_5, which has never been estimated empirically. Exploratory analysis did indicate that very large values of α_5 increase both the optimum r_1 and t_1; the first effect opposes, while the second favors, application of PAS.

These conditions warrant further elaboration. Designing an acquisition program involves making numerous tradeoffs between time and money and the first condition represents one such tradeoff. If the military has an urgent need to implement design modifications, it may elect to accelerate the follow-on development process and compress the schedule. Under most circumstances, however, this would lead to inefficient resource use, thus driving up costs. On the other hand, stretching out this phase would increase the cumulative costs that depend on elapsed time, or schedule length. This corresponds to the second condition. Capital charges and overhead expenses constitute two costs sensitive to schedule length. With appropriate planning, a program may be designed to minimize these costs, thus permitting longer redesign phases without major cost penalties. Finally, the third condition reflects both the scope of required redesigns and how much specific redesign retrofit costs exceed production-line modification costs. This factor depends primarily on the maturity of the initial design and the complexities associated with the retrofit of design changes.

Table 7 has shown the effect of varying the cost function coefficients--α_4, α_6, and $(\beta_1 - \beta_2)$--individually. A large α_4 and small α_6 lead optimally to an extended follow-on development/low-rate production phase; they have, however, a minimal effect on optimum initial production rate. A large $(\beta_1 - \beta_2)$ does reduce the optimum initial production rate. Therefore, to identify programs that might benefit from the PAS approach we should look for cases with a combination of large α_4, small α_6, and large $(\beta_1 - \beta_2)$.

I found one way of varying these three parameters simultaneously that proved useful and straightforward. Starting with the base case values of the three parameters and denoting them by superscript "o", I defined new parameter values as follows:

$$\alpha_4 = \alpha_4^{o} \cdot 2 \cdot F$$

$$\alpha_6 = \alpha_6^{o}/(2 \cdot F)$$

$$(\beta_1 - \beta_2) = (\beta_1 - \beta_2)^{o} \cdot F$$

with F being an arbitrary constant greater than one. By increasing the value of F, $(\beta_1 - \beta_2)$ increases directly with F and α_4 increases twice as fast; α_6, however, decreases, and at the same rate, α_4 increases. By combining these variations, we can explore conditions which favor PAS.

Figure 7a shows how the optimum program initial production rate and phase length vary with variations, as specified above, in α_4, α_6, and $(\beta_1 - \beta_2)$. As the value of F increases from one to seven, the optimum initial production rate declines linearly from 92 to 40 aircraft/year. As F increases to ten, the optimum production rate falls more rapidly to a value of only 2 aircraft/year.

The length of the optimum initial-production phase increases fairly linearly from 0.4 year to 0.6 year as F increases from one to ten. These effects exhibit the anticipated behavior and confirm the applicability of a PAS approach as α_4 and $(\beta_1 - \beta_2)$ increase and α_6 decreases.

Figure 7b illustrates how much program costs deviate from their minimum value when a non-optimum acquisition scenario is employed. The non-optimum scenario has the following characteristics: (1) initial production rate, r_1, equals the full-scale production rate, r_2, of 100 aircraft per year and (2) the initial production phase lasts 0.25 year rather than the optimum length of 0.4 year. This scenario represents an arbitrary acquisition strategy which does not employ a reduced initial-production rate and allows only 3 months for follow-on development. The variable F has the same meaning as described above. As the parameters α_4, α_6, and $(\beta_1 - \beta_2)$ deviate farther from their base case values, the cost penalty for not selecting optimum values of r_1 and Q_1 becomes significantly larger. Total costs equal about \$3.5 billion. When F equals 8, for example, total costs exceed their minimum value by about \$130 million, or 4 percent of total costs.

These results confirm earlier expectations about program features that make PAS a desirable strategy. When retrofit costs exceed production-line modification costs, the optimum strategy requires a low initial production rate, r_1. When the costs of compressing follow-on development increase, the optimum follow-on development phase length

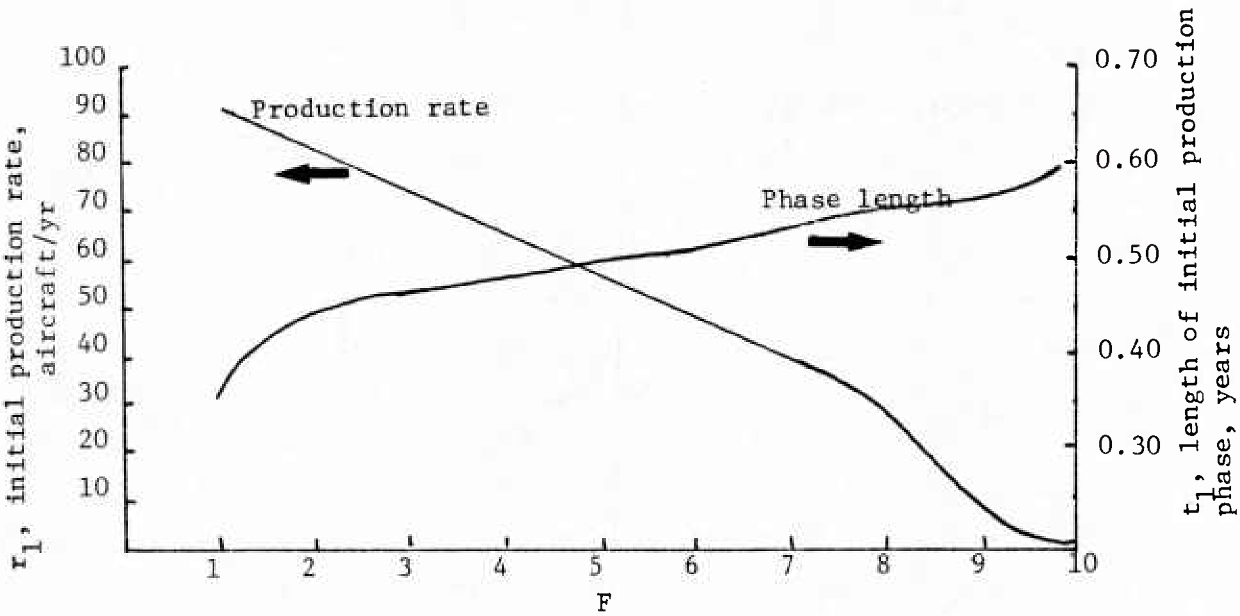


Fig. 7a—Coefficient effects on optimum initial production rate and phase length.

How simultaneous variations in α_1, α_6, $(\beta_1-\beta_2)$ affect optimum initial production rate and schedule length.

$\alpha_4=\alpha_4{}^\circ \cdot 2 \cdot F$, $\alpha_6=\alpha_6{}^\circ/(2 \cdot F)$, $(\beta_1-\beta_2)=(\beta_1-\beta_2)^\circ \cdot F$

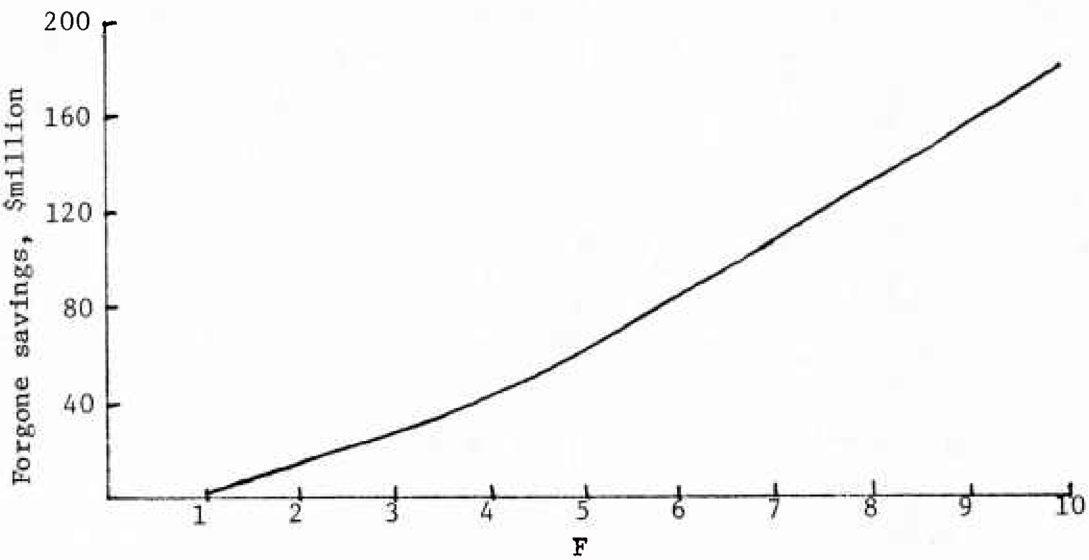


Fig. 7b—Coefficient effects on forgone savings penalty for selecting non-optimum program parameters.

As the factors which make PAS attractive increase with F, the cost penalty for not selecting the optimum production rate and schedule increases significantly.

increases. And, when time-dependent follow-on development costs decrease, the optimum follow-on development phase length increases. These trends lead to an optimum acquisition strategy described as PAS. If the acquisition strategy does not incorporate the optimum values of r_1 and Q_1, the cost penalty increases as the optimum strategy becomes more like a PAS approach.

These observations suggest how to begin evaluating the desirability of applying PAS in a given program. If the initial-production design represents a very immature system, extensive modifications may follow. When the modifications require large expenditures and retrofit costs significantly exceed production-line modification costs, a low initial-production rate appears beneficial. When significant inefficiencies result from compressing the development schedule, follow-on development should be allotted a longer time period. If overhead and other time-dependent costs during follow-on development are not excessive, follow-on development should be extended. Furthermore, the program manager should try to minimize time-dependent costs so that the follow-on development/initial-production phase can be extended a reasonable amount.

The next three sections discuss several actual programs and examine the relevance of PAS to them. They utilize the insights provided by the theoretical discussion in this section.

V. CASE STUDY OF THE C-5A

A. C-5A PROGRAM DESCRIPTION

In late 1965 the Air Force selected, from three competing design proposals, a Lockheed design for a large cargo aircraft with the capability to economically carry oversize military equipment. Though an exceptionally large aircraft with demanding performance requirements, the C-5A program guiding principle emphasized conservatism in some areas to avoid pushing the state-of-the-art. Because of its confidence in the basic design feasibility and its desire for rapid operational capability, the Air Force conducted the program under a Total Package Procurement (TPP) contract. This required a firm contractor bid for both development and the first production lot, extensive performance guarantees, restrictions on engineering change proposals, and considerable concurrency of development and production.

Figure 8 shows the C-5A program schedule, major events, and the aircraft delivery schedule. Since the program incorporated extensive development-production concurrency, the figure shows production build-up during early development. The first aircraft delivery occurred in early 1968 and the first flight took place shortly after. After production of the sixteenth aircraft, the production rate increased to the full-scale rate of about two aircraft/month. Production continued until June 1973 when the eighty-first aircraft delivery occurred.

Figure 9 shows the C-5A program expenditures over time.[1] The costs shown include only airframe items and exclude engines which GE produced under a separate contract. The overlap of development and production activities made it difficult to separate the costs of the two. Clearly, during the first few years expenditures went primarily into development activities. The expenditure rate increased significantly during 1969, when production began to increase. The expenditure

---

[1] All costs throughout this paper are in 1975 dollars.

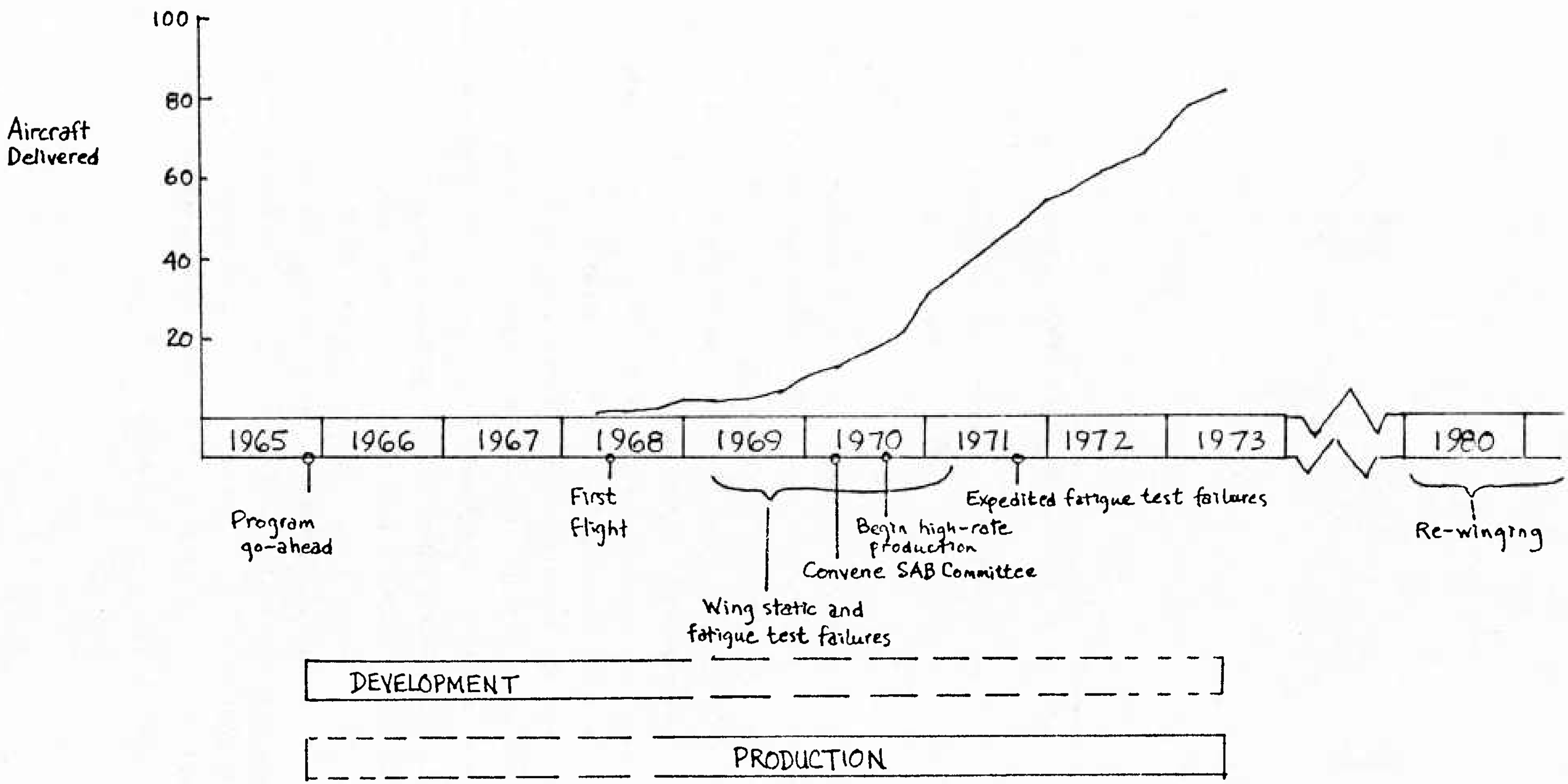


Fig. 8—C-5A program schedule and major events

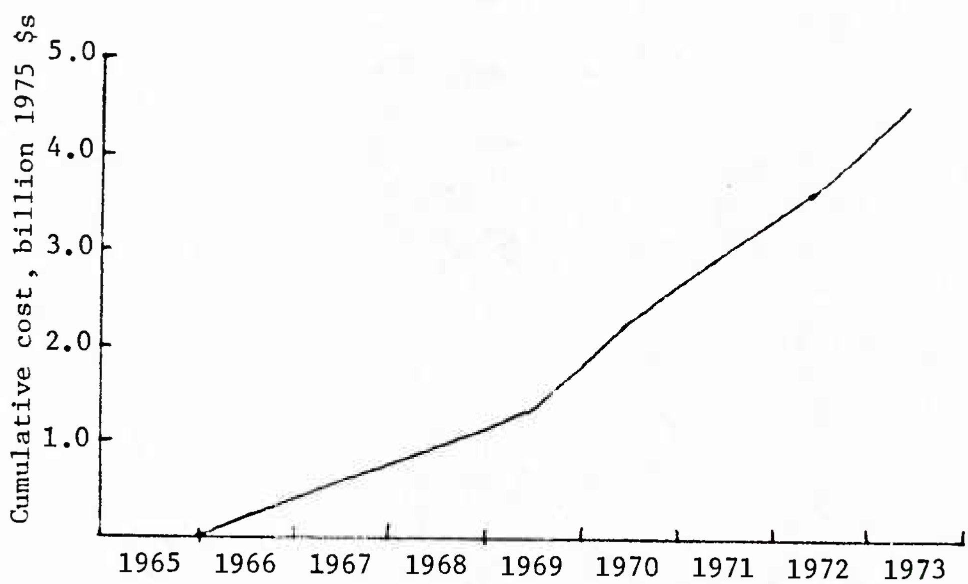


Fig. 9—C-5A airframe program cost vs time

rate remained fairly constant through the end of production in mid-1973. As an approximate figure, C-5A development cost about $1.2 billion, production cost roughly $3 billion, and initial spares cost about $0.24 billion, for a total program cost of about $4.5 billion.

Figure 8 shows several of the major events in the C-5A program and emphasizes those associated with the key C-5A design problem, understrength wings. Considerable controversy has surrounded this problem and the analysis here has avoided many of the controversial issues related to it. This analysis has simply treated the wing deficiencies as a design issue, and has explored other approaches for dealing with the problem, through the acquisition program structure.

As early as mid-1969, ground tests began revealing potential wing weaknesses. The initial static test item failed at 85 percent of its objective. In January 1970, inspections revealed wing cracks on one of the flight test aircraft. Early in 1970, the Air Force convened a special Scientific Advisory Board (SAB) panel to review C-5A problems. In mid-1970 the SAB reported on a number of aircraft problem areas and cautioned that the wing required more testing and probably

would experience strength deficiencies. In October 1970 the fatigue test program revealed wing fatigue failure at 9,000 equivalent flight hours. This constituted only 30 percent of original specified service lifetime of 30,000 hours. Over the next two years, evidence of the wing deficiencies mounted; nevertheless, aircraft production continued and finished with the eighty-first aircraft in 1973. A total rewinging effort began in 1980, at a cost in excess of one billion dollars.

Many features of the C-5A program, not the least of which were extensive concurrency and schedule pressures, contributed to the evolution of this problem. Though initial structural testing occurred fairly early in the program, the Air Force had already accepted five aircraft by the time initial test results indicated a potential deficiency. Production continued as evidence mounted, and no significant changes occurred in the C-5A design. Thus, even though the test program produced information, the production program failed to take advantage of it at an early date. The program momentum continued to build, and no major decisions about wing redesign occurred until after all aircraft had been produced.

In terms of the wing problem alone, the C-5A program appeared to be a good candidate for the PAS approach. A delayed transition to high-rate production and a planned redesign phase would have had potential for significantly improving program outcomes.

B. STRUCTURING THE C-5A AS A PAS PROGRAM

The theoretical acquisition model, developed earlier, provides a description of several phases and mechanisms in the acquisition process. It models the relationships among initial production rate, follow-on development, full-scale production rate, and program costs, for a given effectiveness level. Though universal considerations in all acquisition programs, these relationships and their importance would vary from program to program.

One major problem dominated C-5A design deficiencies and its

initial identification resulted from ground tests.[1] The dominance of one problem differed from the situation described by the model. Problem identification through ground testing also differed from the basic model construct.

In other ways the C-5A program demonstrated compatibility with the theoretical model structure. The program contained an initial, though relatively brief, low-rate production phase during which flight testing and continued development occurred. The full-rate production phase followed the initial production phase, and production increased rapidly to a fairly constant level. A major retrofit has begun in the rewinging activity, but this has not been paralleled by a wing production-line modification.

In terms of the effectiveness measure, the C-5A program differed from the assumption made in the model. In the model, the aggregate effectiveness level would reach its maximum level at the end of production and would remain constant until aircraft retirement began. In the actual C-5A program, individual aircraft effectiveness fell far short of initial specifications because of the drastic shortfall in wing lifetime. The effectiveness level remains diminished until rewinging has occurred. In actual practice, the wing deficiency has decreased the daily operating rate and has imposed load limits on the aircraft. An attempt to quantify the economic costs of these effectiveness shortfalls would entail major methodological and philosophical issues not within the scope of this research. The effectiveness issue will receive some, but not complete, coverage in the two following sub-sections.

This research uses a simulation approach to explore acquisition strategy effects on C-5A program outcomes. The C-5A program had an initial production phase, during which the production rate remained relatively low. Simultaneously, ground and flight testing occurred which provided information about system deficiencies, particularly

---

[1]Note that the two subsequent case studies include many design deficiencies managed through Engineering Change Proposals, ECPs. The Air Force maintained no extensive ECP data base in the C-5A program and the wing deficiency dominated modification costs so this analysis has been restricted to this one major deficiency.

wing problems. The simulation analysis retrospectively extends the initial, low-rate production phase, while this information accumulates. The simulation analysis operates under the assumption that an alternative C-5A acquisition program could have delayed high-rate production until testing had identified the wing problems and development had produced an improved design. The simulation thus delays high-rate production until a wing redesign will be ready for production-line and retrofit installation. In the last step, the simulation analysis increases production to the full-scale rate. With suitable functions and assumptions, the simulation also produces estimates of the costs associated with these different activities.

C. PROGRAM ANALYSIS APPROACH

The categories in the narrowed theoretical acquisition framework include these: initial production, follow-on development, extra operating, full-scale production, and retrofit and production-line modification costs. Only extra operating costs did not need to be included in the C-5A simulation analysis because ground tests, rather than operating experience, provided most information about C-5A wing deficiencies. The analysis includes each of the other cost categories, within constraints imposed by data availability and analytic methodology.

Initial-Production and Full-Scale Production

In the C-5A program simulations, the initial and full-scale production phases differ in production rate and, most importantly, the wing design which is being installed. The first part of this sub-section discusses an indirect method for determining the production rate effects on total program production costs. The second part develops an approach for estimating production costs for the original wing design.

One way to estimate production-rate cost effects requires an estimate of actual program costs. Available data sources have broken program costs into recurring and non-recurring costs.[1] Non-recurring costs come primarily from development activities and recurring costs come largely from production activities. Of the $4.5 billion C-5A airframe costs, about $3.46 billion

[1] The C-5A costs presented here originated in unpublished Rand research.

constitute recurring costs. Previous research has determined that only overhead costs depend significantly on program length and, therefore, production rate.[1] This earlier research establishes the following relationship for a broad range of programs:

$$OH = 9.68 + 0.299 \cdot TRC \tag{24}$$

where

OH = annual overhead cost, million 1975 \$/year,

TRC = annual total recurring cost, million 1975 \$/year.

Since TRC includes overhead cost, overhead cost can be eliminated from the right-hand side of Eq. (24) to determine overhead in terms of non-overhead recurring costs, viz:

$$OH = 13.81 + 0.427 \cdot RC \tag{25}$$

where

RC = annual recurring costs excluding overhead, million 1975 \$/year.

The average annual total recurring cost, TRC, over the seven-and-a-half year program equals about $361 million. Equation (24) estimates average annual overhead costs, OH, at $148 million. Thus, total program overhead costs are about $1.11 billion and other program recurring costs are about $2.35 billion.

The observations above derive from the assumption that total program recurring costs, excluding overhead, do not vary with program length. Only total overhead expenditures would depend on program length. Under these conditions, Eq. (25) multiplied by program length should give total program overhead costs. However, the second term on the right-hand side, times program length, equals total program recurring costs excluding overhead; under our assumption

---

[1] Large, J. P., K. Hoffmayer, and F. Kontrovich, *Production Rate and Production Cost*, The Rand Corporation, R-1609-PA&E, December 1974.

this quantity always equals \$2.35 billion. Therefore, total program overhead costs vary with program length only through the constant term, \$13.81 million per year. Thus, total overhead and production cost for the whole program would increase, with program length, \$13.81 million per year, or \$1.2 million per month.

To account for the level of effort in the C-5A program and treat the effects of program stretchout conservatively, cost estimates could also include estimated additional sustaining engineering expenditures. Actual C-5A monthly engineering expenditures, excluding overhead, range from about \$3 to \$5 million. If a stretchout had occurred and the program did incur additional engineering costs, they probably would have accrued at a rate lower than in the actual program since not all engineering activities would have increased. Taking the midpoint of the engineering cost range from the actual program I have estimated engineering stretchout costs at half this value, or about \$2 million per month. If engineering costs had increased as a result of program stretchout, then the total incremental costs, including additional overhead, would have been about \$3 million per month.

Though this approach has not directly addressed the effects of production rate on production cost it has provided a way of estimating such effects. PAS would extend the initial low-rate production phase and, if the full-scale production rate were unchanged from the actual program rate, the entire production program. The initial production rate and length of the initial production phase would determine the extent of the program stretchout. The above analysis indicates that airframe production costs can be estimated by simply comparing the length of the alternative program to the actual C-5A program length and adding, to the actual program cost, \$3 million per month of additional program length.

The costs of installing the original wing on aircraft during production would constitute one significant cost component in each alternative C-5A acquisition scenario. The magnitude of these costs would depend on the number of aircraft produced with the original

wing. In the actual program, all 81 aircraft had the original wing installed during production. A Rand cost model has provided an estimate of average C-5A production costs which equaled \$133 per pound of airframe.[1] To estimate original wing production costs, this analysis assumes that this average cost applies to the wing as well. Since the original wing weighed 82,745 pounds, the estimated costs of producing the 81 original wings equals \$891 million. In alternative programs fewer aircraft would be produced with the original wing, and this cost component would contribute less to total costs.

Estimating the cost of producing fewer original wings introduces the concept of the learning curve. Observations have shown that the labor required to produce an additional unit falls as the number of units increase.[2] Thus, marginal production costs would decrease as the total number of production units increases, and thus, total costs would increase less than linearly with the number of units produced.[3] The learning curve slope would indicate the amount marginal costs decrease. The learning curve slope would differ for different kinds of activities. A typical learning curve slope for the production process contemplated here would equal about 80%. This indicates that the marginal production cost of the 2k-th unit would equal 80% that of the k-th unit. Table 9, below, shows the effect of an 80% learning curve slope on marginal and cumulative costs.

Using the learning curve properties above permits making estimates of the costs of producing fewer than the 81 original wings. Dividing the \$891 million total cost by the relative cumulative cost for 81 wings, from Table 9, gives the cost of producing the first

---

[1] From unpublished Rand research.

[2] See, for example, Large et al.

[3] This would correspond to an exponent less than one on the second term, Q, in the production cost functions Eqs. (10) and (11). In the theoretical model formulation, the total production quantity did not vary, so neglecting the learning curve effect did not influence the optimization process. Note that this effect differs from the effect of production *rate* on production costs.

Table 9

MARGINAL AND CUMULATIVE COSTS
WITH 80% LEARNING CURVE SLOPE

Unit	Relative Marginal Cost	Relative Cumulative Cost
1	1.00	1.00
10	0.48	6.32
20	0.38	10.48
30	0.34	14.02
40	0.31	17.19
50	0.28	20.12
60	0.27	22.86
70	0.26	25.46
80	0.24	27.95
81	0.24	28.19

original wing. Working the process in reverse, multiplying the first original wing cost by the relative cumulative cost, for the number of original wings produced in a given alternative scenario, gives an estimate of the cost of producing these original wings, in that scenario. For example, if an alternative scenario includes the production of 20 original wings, then this cost component would equal 10.48 times the cost of producing only one original wing. Thus, this methodology provides a technique for estimating the original wing production costs in a program, such as possible PAS scenarios, in which fewer than 81 aircraft have the original wing installed.

Follow-On Development

In this analysis, the follow-on development activity of primary concern consists of the design and fabrication efforts that went into the C-5A rewinging program. In the actual program, most of the work occurred after completion of the basic C-5A program. In the alternative strategies considered here, this activity would occur well before the end of C-5A production.

Available information indicates how the rewinging activity will occur, according to current plans. This information provides a starting point for evaluating the rewinging, if it had happened dur-

ing C-5A production, but, of course, this information does not provide very reliable estimates of schedule and costs of this quite different alternative.

The primary C-5A rewinging plan has a 48-month schedule for developing, designing, and beginning installation of the first redesigned-wing unit.[1] The cost of the rewinging program includes an estimated $130 million for development.[2] In the context of this analysis, the $130 million constitutes the follow-on development cost associated with the wing modification.

Available references provide no information about the effects of follow-on development schedules on costs. However, the rewinging plan described above minimizes concurrency between redesigned-wing development and installation, while other plans reviewed by the Air Force include more concurrency. Thus, the development schedule described above could have been shortened, and the development costs might decrease under a more concurrent plan. For present purposes, the described rewinging plan constitutes the base case.

The base case follow-on development characteristics provide a starting point for analyzing alternative C-5A acquisition programs. The analysis uses the $130 million development cost in all alternative acquisition cases. Without any estimates of schedule effects on rewinging development costs, this analysis relies on the assumption that these costs would be relatively insensitive to modest schedule variations. In terms of schedule, the planned rewinging development appears fairly unpressured. In a C-5A program in which the rewinging occurs during aircraft production, it might be beneficial to accelerate the rewinging development. Furthermore, since basic program development would still be active, the rewinging development would not consume any start-up time. Thus, in all likelihood, rewinging follow-on development would require significantly less time in an alternative program, where this development happens during the pro-

---

[1] *Competition Feasibility Study for C-5A Plan "H" Wing Modification, App. F*, Air Force Aeronautical Systems Division, January 25, 1975.

[2] *Aviation Week & Space Technology*, January 25, 1975.

gram, than in the current program where it happens several years after production has terminated.

Production-line Modifications

In this study, one major activity in alternative acquisition scenarios consists of installing the redesigned wing during production. In the actual program this never happened since all modifications take place through retrofit. The scenario characteristics determine when redesigned wings become available on the production line and, thereafter, all production aircraft have the redesigned wing.

The weight of the redesigned wing provides one cost estimate. The wing weighs 97,386 pounds. This study assumes that this wing, if installed from the beginning of production, would cost the same amount per pound as the estimated C-5A airframe cost of $133 per pound. Thus, the estimated total redesigned wing cost would equal $1,049 million for 81 aircraft.

The learning curve property would also affect the cost of installing the redesigned wing on the production-line. The above estimate and the learning curve relationships, illustrated by Table 9, permit an estimate of the marginal cost of installing the first redesigned wing on the production line. In the scenarios considered here, production-line installation of the redesigned wing follows production of several aircraft built with the original wing. It appears very reasonable to assume that learning would carry over from production of one wing design to the other, since the designs have several features in common. In the cost estimates discussed later, the assumption has been made that learning which occurs during production-line installation of the original wing carries over to production-line installation of the redesigned wing.

Wing Retrofit Modifications

A prior estimate places the C-5A rewinging cost at $897 million for 77 aircraft.[1] This quantity includes $130 million for development.

---

[1] *Aviation Week & Space Technology*, April 28, 1975, p. 30.

Thus, estimated rewinging production costs equal \$767 million for 77 aircraft. For consistency, this study has adjusted the value to \$794 million for a fleet of 81 aircraft.[1]

For wing retrofit of fewer aircraft, the learning curve effects should apply again. This study has used the learning curve relationships discussed earlier to estimate the cost of performing the first rewinging. Then, using the relative cumulative cost, from Table 9, for the appropriate number of aircraft retrofit, this analysis has estimated the total rewinging cost for alternative acquisition scenarios.[2]

Cost Analysis Methodology

The available data provide a good foundation for analyzing the effects of acquisition strategy on wing modification costs in the C-5A program. Since the wing modification program has been extensively studied, previous analyses have provided fairly reliable information about wing retrofit costs. Previous research on production learning curves provide information useful for estimating rewinging costs in the alternative acquisition scenarios, in which only a subset of the C-5A fleet would require wing retrofit. Previous research also provides information useful for estimating the costs of installing the redesigned wing during C-5A production.

The two primary program variables in this analysis consist of (1) the length of time required to identify the wing deficiency, and (2) the length of time required to develop and begin installing the redesigned wing. The analysis does not treat the initial production rate as a variable, but simply takes the initial production rate in the actual program and maintains it until redesigned wings become available in each alternative scenario. The model does not explore

---

[1] Four C-5A aircraft have been lost through attrition.

[2] Note that this approach does not assume learning carries over from the production line to rewinging. Since it very well might, in a program where rewinging occurs immediately after production has ceased, the cost savings estimated later represent conservative estimates when compared to the actual C-5A program where several years lapsed between program termination and rewinging.

production-rate variations because, basically, the actual initial rate was about as low as practicable. Furthermore, identification of the wing problem occurred through ground testing so the link that the theoretical model assumes between the deficiency and flight experience does not apply.

Though the theoretical model does not use time as a basic variable, its basic variables relate directly to time. In the theoretical formulation, the ratio of the decision variable Q_1--the initial production quantity--to r_1--the initial production rate--determines the length of the initial production phase. In our formulation of C-5A program scenarios, r_1 stays constant and the length of the production phase varies, thus varying Q_1. The C-5A cost simulation analyses start with best estimates of these two time parameters.

In terms of wing modifications, the actual C-5A program has consisted of the production of 81 aircraft with the original wing, followed, several years later, by rewinging of all 81 aircraft.[1] The total C-5A wing-related cost equals the sum of the costs of these two activities. From an earlier sub-section, the estimated production costs of all 81 original wings equals \$891 million. Also from an earlier sub-section, the estimated retrofit cost of rewinging 81 aircraft equals \$794, plus development costs of \$130 million. For present purposes, this analysis considers only manufacturing cost components, and assumes rewinging development costs would not vary under different scenarios. Thus TC_{BC}, the actual program, or base case, costs would be

$$\begin{aligned} TC_{BC} &= \$891 \text{ million} + \$794 \text{ million} \\ &= \$1{,}685 \text{ million.} \end{aligned}$$

Alternative C-5A acquisition scenarios would partially include the two activities above, plus some production-line installation of

[1] In actuality, only 77 aircraft remain in the fleet, but this analysis uses 81 aircraft in all estimates for consistency.

redesigned wings. The learning-curve process would affect each of these activities. Appendix C presents the details of the methodology for estimating alternative program costs.

D. C-5A PROGRAM ANALYSIS AND RESULTS

The theoretical framework developed in Section III provides a foundation for analyzing alternatives to the actual C-5A acquisition program. It includes the initial, low-rate production phase during which development continues; this continuing development identifies problems and leads to their solutions. In the actual C-5A program an initial, low-rate production phase in conjunction with on-going tests and demonstrations, began to identify the wing deficiencies. The theoretical framework also defines and outlines the modification process; in the actual C-5A program a major, well-defined modification effort constitutes one of its most outstanding features. The theoretical framework explores the crucial costs throughout this acquisition phase; this analysis has developed cost relationships for the activities in alternative C-5A scenarios.

In some ways, however, the theoretical framework does not coincide well with characteristics of the C-5A program. The general difficulties of defining effectiveness, and the fact that effectiveness delivered in the actual C-5A program fell far short of program goals, prevent a direct transfer of the theoretical framework's effectiveness concepts to the C-5A scenarios. The scenario analyses do, however, explore some effectiveness impacts. The available program information does not allow the scenario analyses to treat production rate effects in precisely the same way as the theoretical framework.[1] However, the analytic methodology indirectly includes the possible cost effects of production rate. Though these restrictions do not permit the C-5A scenario analyses to adhere strictly to

[1] Note that a refinement of the theoretical model would have allowed coefficients in the production cost functions to differ between the low-rate and high-rate production phases. In this case, the theoretical model would have been consistent with the earlier assertion that production cost penalties need not occur if an initial, low-rate production phase were properly designed.

the theoretical framework, the analyses do explore cost and effectiveness outcomes over a range of program alternatives. By so doing, the analyses show which program characteristics affect outcomes the most and to what degree.

Two schedule parameters characterize each scenario--(1) how long it takes to identify the wing deficiency, and (2) how long it takes to develop the wing redesign. The various cases treat these parameters as sensitivity variables.

In all alternative cases, the initial, low production rate--one aircraft per quarter--continues until redesigned wings become available on the production line. Thereafter, production rate reaches two aircraft/month and remains there until production of the eighty-first C-5A. Though the analytic methodology does not explicitly include possible effects of production rate on production cost, it does so indirectly through variations in possible stretchout costs.

Table 10 presents a summary of cost results. Case 1 shows the features and costs in the current program. This program includes no redesigned-wing production costs since all redesigned wings will be installed through retrofit. Total costs equal $1,685 million for the current program. Case 2 illustrates a representative PAS case: wing redesign starts in July 1970 and requires three years. No stretchout penalties occur in this case, under the assumption that appropriate planning would control the costs during the anticipated low-rate production phase. Since the original wings would be installed on only 21 aircraft, both original-wing production and redesigned-wing retrofit costs fall significantly relative to the actual program. Installation of redesigned-wings on the production line, however, add costs of $645 million. On balance, total costs fall $391 million relative to the actual program.

Cases 3 through 8 illustrate the effects of the key sensitivity parameters on costs, relative to the representative phased acquisition case. Cases 3 and 4 show how variations in the wing-redesign start date affect the costs. Delaying the redesign start one year adds four aircraft requiring wing retrofit, and decreases savings to $358 million; advancing the redesign start date by one year subtracts four

Table 10

C-5A ANALYSES RESULTS

Case Description	Current Program	Representative PAS Program	Vary Redesign Start Date		Vary Redesign Time		Vary Stretchout Costs	
Case Number	1	2	3	4	5	6	7	8
Redesign Start Date	Apr 75	Jul 70	Jul 71	Jul 69	Jul 70	Jul 70	Jul 70	Jul 70
Redesign Time (Months)	48	36	36	36	60	30	36	36
Stretchout Cost ($ million/month)	--	0	0	0	0	0	3	6
Redesigned Wing Retrofit Costs ($ millions)	794	306	347	263	386	285	306	306
Original Wing Production Costs ($ millions)	891	343	389	295	432	319	343	343
Redesigned Wing Production Costs ($ millions)	0	645	591	702	540	673	744	843
Total Costs ($ millions)	1,685	1,294	1,327	1,260	1,358	1,277	1,393	1,492
Savings ($ millions)	--	391	358	425	327	408	292	193

aircraft requiring retrofit, and increases savings to \$425 million. Cases 5 and 6 show the cost effects of varying the amount of time required to redesign the wing. Increasing the redesign schedule to five years adds eight aircraft in need of retrofit, and reduces savings to \$327 million. Shortening the redesign schedule to 2-1/2 years decreases the aircraft requiring retrofit by two, and increases savings to \$408 million. Finally, Cases 7 and 8 show how stretchout cost penalties could cut into potential savings. Without planning to accommodate low-rate production stretchout, a cost penalty of about \$3 million per month of program extension seems most reasonable. Since the representative phased acquisition case, Case 2, involves a 33-month program extension, savings would fall by \$99 million, to \$292 million, as shown by Case 7. If a higher penalty, \$6 million/month occurs, then savings would be only \$193 million.

Alternative acquisition strategies also would produce different program effectiveness outcomes. No universally accepted effectiveness measure is available for evaluating effectiveness impact in the C-5A program. Two quite different measures seem appropriate to explore different effectiveness characteristics. One metric reflects primarily the quantity of aircraft available. Since the quantity of cargo aircraft would have most importance in times of sudden airlift demand I have called this metric *surge effectiveness*. The second metric depends on the long-term ability of the C-5A to provide airlift capability. Since long-term operations would depend on inherent structural lifetime, especially of the wing, this metric varies significantly across programs that produce different mixtures of original and redesigned wings. I have called this measure *sustaining effectiveness*.

Figure 10a compares the surge effectiveness in the actual and representative PAS programs. Through the first five aircraft, or up to about mid-1969, the two programs would coincide. Thereafter, aircraft deliveries in the phased acquisition scenario would fall farther behind those in the actual program until delivery of the twenty-first C-5A, which occurs in early 1970. From then on, deliveries in the PAS program would occur about three years later than they did

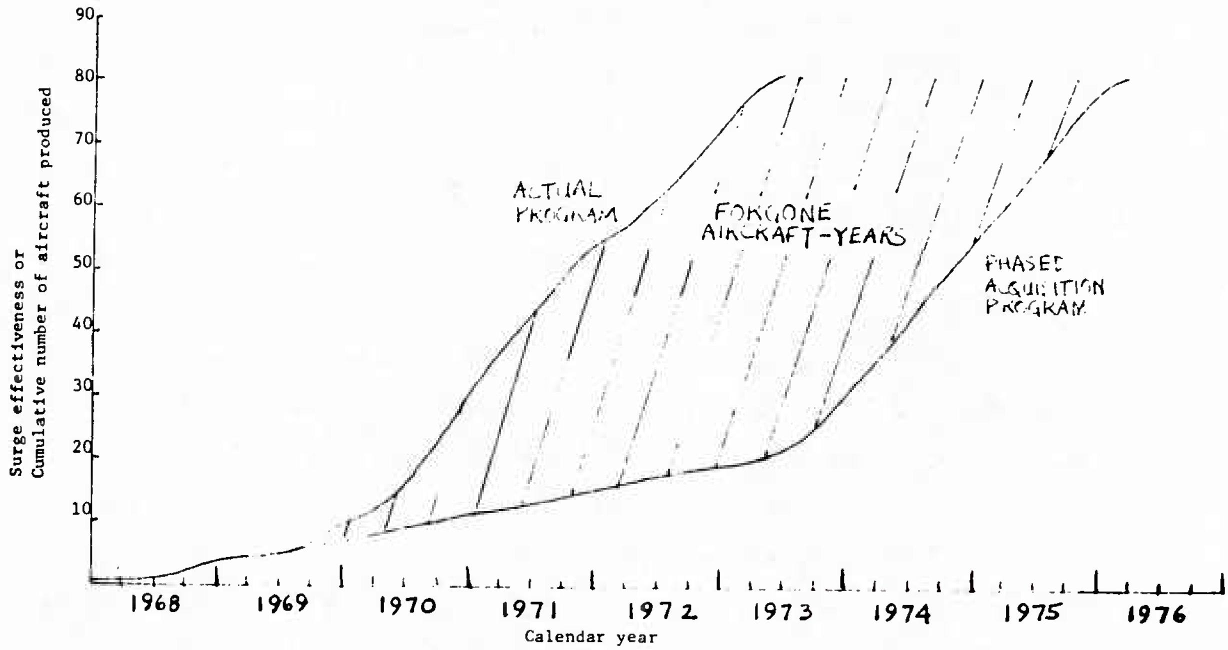


Fig. 10a--C-5A surge effectiveness (quantity of aircraft produced)

The actual C-5A program delivered more aircraft early in the program than would the PAS program, thus providing more early surge effectiveness. The cross-hatched area indicates the net difference between aircraft-years supplied early in the two programs.

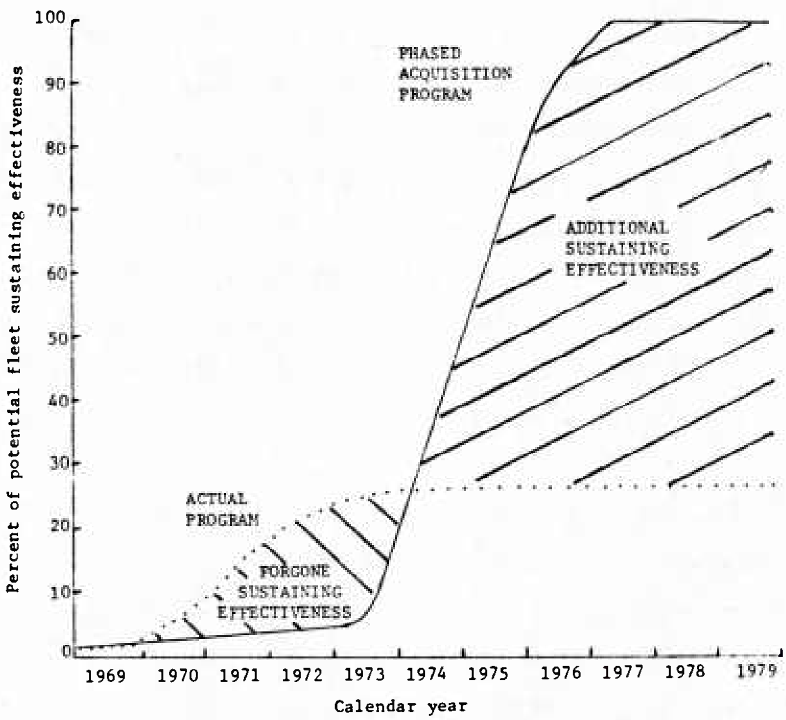


Fig. 10b--Sustaining effectiveness in C-5A actual and phased acquisition programs

The actual C-5A program provides more early sustaining effectiveness than would the PAS program, but the PAS program provides for more sustaining effectiveness after 1973.

in the actual program. This means that, if high airlift capability had been required in the 1972-1973 period, the phased acquisition program would have been unable to supply it, while the actual C-5A program could have. However, if only modest C-5A airlift capability had been required the phased acquisition approach would have performed satisfactorily.

Figure 10b compares the sustaining effectiveness levels in the two alternative program scenarios. Sustaining effectiveness has been defined using original C-5A design goals--wing lifetime should equal 30,000 hours and daily flight rate should equal 5 hours. Under these conditions each C-5A would provide service for 16.5 years. To calculate sustaining effectiveness levels, the analysis assumes that daily flight-rate would be adjusted to permit the aircraft to last 16.5 years. Thus, permissible daily flight-rate levels would have to fall with reduced wing service lifetimes. Figure 10b shows that the phased acquisition program would deliver less sustaining effectiveness than the actual program did until early 1974. Thereafter, as redesigned wings with 30,000-hour lifetimes become available, the sustaining effectiveness in the phased acquisition scenario would rapidly exceed levels in the actual program. Thus, in terms of providing aircraft capable of intensive service, on a routine basis, the phased acquisition approach would perform quite well.

E. C-5A CASE STUDY SUMMARY

Characteristics of Actual Program

The C-5A program involved fairly modest technological advance but made inadequate use of acquisition strategy as a means of resolving technical uncertainties. Though the largest cargo aircraft built, most observers at the time felt the design required no major breakthroughs. Reflecting, in part, this perceived technical tractability, the Air Force employed the TPP contracting approach, which led to considerable development-production concurrency, and minimal Air Force involvement in design decisions. Consequently, the program received an early production commitment and, in spite of early negative

test results, it proceeded without serious considerations of possibly salutory system redesigns.

This approach led to rapid delivery of a severely deficient aircraft. First flight followed program go-ahead by about two and a half years and production increased quickly to the full-scale production rate. Though the major deficiency, understrength wings, became progressively more urgent, production continued at high rates until the program was terminated. The wing problem has restricted C-5A capability and reduced the wing service lifetime to less than a third of the original lifetime goal. The Air Force has recently initiated an extensive, costly, wing retrofit program to increase service lifetime.

Expectations Based on Research Findings

Previous acquisition research has highlighted the dangers of program concurrency when significant design uncertainties occur. Though not extremely technically challenging, the C-5A design did pose serious technical risk when combined with a highly concurrent acquisition program. The actual C-5A acquisition program could have delivered a successful product if all component designs reflected readily available technology. The acquisition program, however, allowed no time or options for the resolution of serious design problems. Even though limited tests did warn of wing strength deficiencies, the production commitments and preparations provided strong incentives to move into high-rate production and underestimate eventual impacts of unresolved deficiencies.

The theoretical model developed here has suggested that the C-5A would have been a good candidate for PAS. The model predicted large cost reduction potential when design deficiencies necessitate costly retrofit; the C-5A certainly fell into this category with current retrofit cost estimates exceeding one billion dollars. The model also demonstrated larger advantages of PAS if *stretchout costs* have been minimized. Clearly, C-5A program managers made no attempt to minimize stretchout costs, such as overhead and sustaining engineering; if they had, however, the C-5A could have benefitted even more from PAS through

reduced development and production costs, as well as reduced retrofit costs. Furthermore, the model suggested that PAS would reduce costs more if *schedule compression costs* were high. We had no way of assessing how much schedule compression increased C-5A program costs, but at least one reference has provided anecdotal and quantitative evidence of inefficiencies in the program.[1]

This current research also has suggested a PAS approach would have offered potentially large improvements in system effectiveness. In the C-5A program, we would have expected PAS to delay high-rate delivery but increase the capability of individual aircraft.

Overall, previous and current research would have led us to expect that the C-5A could have benefitted from a PAS approach. The design involved crucial, though not widespread, design uncertainties; the program involved extensive concurrency and allowed little scheduling flexibility; the program contained insufficient testing and made poor use of test data; and, the program involved inadequate interaction between the Air Force and system designer.

PAS Effects

This case study has estimated how PAS would have affected the C-5A program. It has utilized the length of two key activities to define alternative acquisition strategies, given that the program incorporated an extended low-rate production phase. Since the length of these activities involved considerable estimation uncertainties, the analysis treated them as sensitivity parameters. These parameters were (1) the time required to identify the wing deficiency and (2) the time required to develop a wing redesign. The representative PAS case had the following characteristics:

- o The wing deficiency identification occurred 4-1/2 years after program go-ahead, and
- o wing redesign required three years.

---

[1]Fitzgerald, A. Ernest, *The High Priests of Waste*, W. W. Norton & Co., Inc., New York, 1972.

This representative PAS case produced the following results:

- o program costs decreased \$391 million,
- o low-rate production extended an additional 2-1/2 years, and
- o long-run effectiveness increased substantially.

The cost reduction represented about 10 percent of total program costs. The low-rate production extension would have reduced the early inventory size. The early incorporation of redesigned wings, however, would have produced a more capable aircraft nearly eight years sooner than the actual program did.

In this case, this analysis has shown that PAS could have reduced C-5A program costs significantly. Additionally, it would have provided the Air Force with a more capable aircraft, able to provide higher levels of effectiveness for an interim period of eight years. It would have reduced, however, the number of aircraft available early in the program.

VI. CASE STUDY OF THE F-111

A. F-111 PROGRAM DESCRIPTION[1]

Program Overview

The F-111 aircraft represented one of the most challenging military system developments of the last three decades. The program encountered serious political, as well as engineering, difficulties. Its origins can be traced to a 1960 decision by Secretary of Defense McNamara to develop one aircraft type to satisfy rather disparate Air Force and Navy requirements. Though the Navy eventually succeeded in withdrawing from the program, after years of opposing it, the multi-mission nature of the initial requirements continued to plague the F-111 design.

The demanding requirements led to an aircraft design that pushed the state-of-the-art in engine, wing, and avionics technology. The F-111 represented the first application of an afterburning turbo-fan engine to a combat aircraft. The great variety of missions envisioned for the F-111 required the first application of a variable-sweep wing to an operational aircraft. And, the planned long-range flight capability and desired navigation accuracy required a sophisticated set of unproven avionics subsystems.

The increasing need for combat aircraft in Vietnam significantly influenced the F-111 program. Once the F-111 had demonstrated its potential capabilities in 1967, the program came under considerable pressure to deliver substantial quantities of aircraft for deployment in Southeast Asia.[2]

Figure 11 provides an overview of the F-111 program.[3] DoD gave the program go-ahead in December 1962 and General Dynamics began flight tests of the first prototype two years later. Before it had received any test data, however, the Air Force issued a production contract in April 1965. Shortly thereafter, ground tests and flight tests began

---

[1]See Coulam, Robert, *Illusions of Choice*, Princeton University Press, Princeton, New Jersey, 1977, for an excellent, detailed description of the F-111 program.

[2]Knaack, p. 228.

[3]Total program costs were about $9.6 billion, in 1975 dollars.

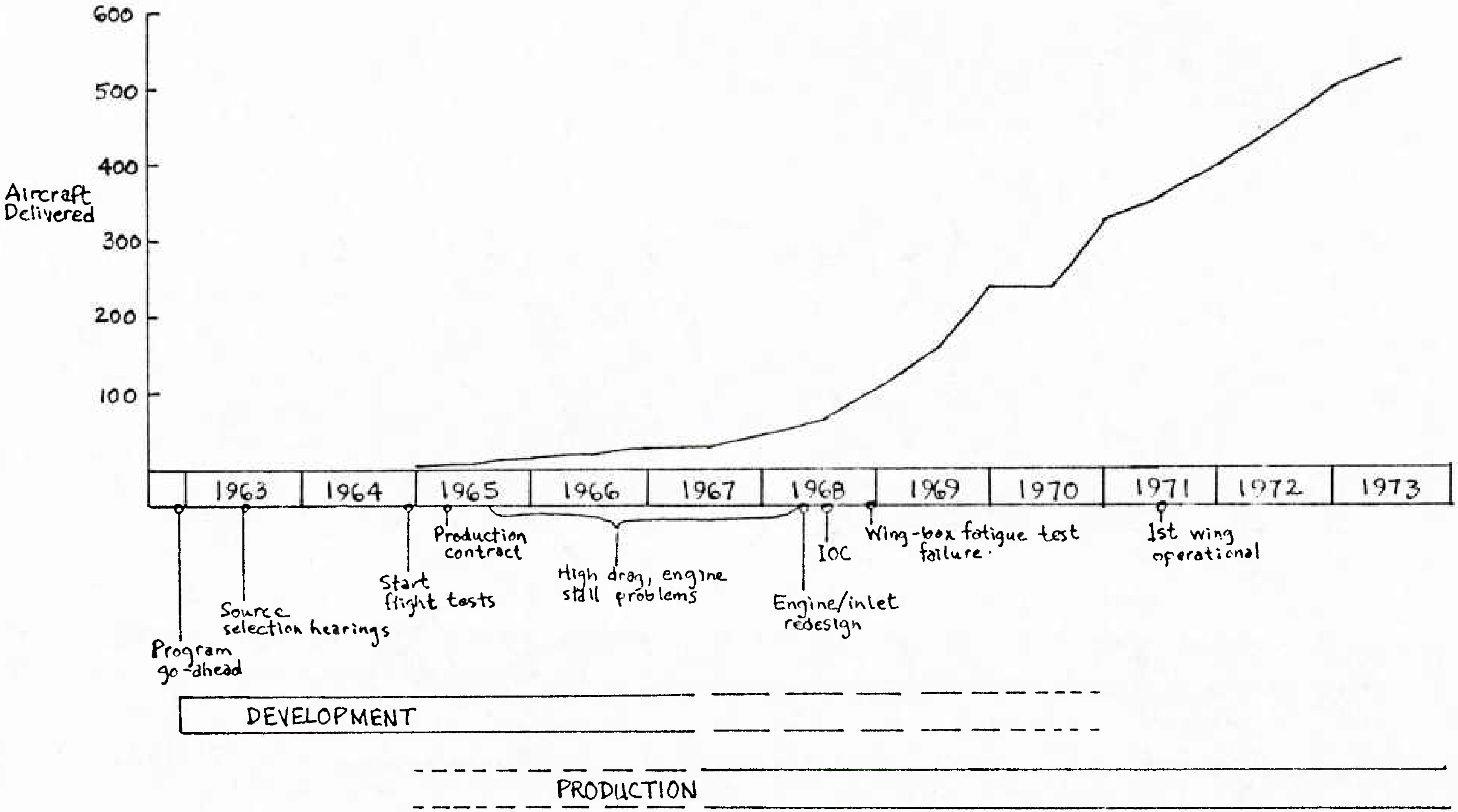


Fig. 11--F-111 program schedule and major events

to reveal serious deficiencies related to the engine--a substantial amount of engine stalling (a loss of power or complete shutdown) occurred. Aircraft weight had grown before this period and continued to grow, and flight tests revealed excessive drag. The stalling problem restricted the flight test program, thus delaying the generation of flight test data. In late 1968 the fatigue test program revealed a serious strength deficiency in the wing box, a key element in the sweep-wing design. Even as these problems surfaced, however, production continued and production rate increased.

These serious problems eventually led to major design changes. The stalling problem required substantial engine modifications and an entire redesign of the engine inlet structure. But these solutions came along so late, and the retrofit costs would have been so large, that the first 141 F-111s were never modified as required. The weight-growth and drag problems necessitated higher engine thrust, and later aircraft eventually incorporated adequately redesigned engines. And, the wing-box problem led to production-line modifications and a $100 million retrofit program.[1]

One Perspective on the F-111 Program

The F-111 requirements necessitated significant, simultaneous performance improvements in several areas but, in spite of this, the F-111 program contained a considerable degree of concurrency between production and development. In retrospect, the major problems and their late resolution seem almost inevitable.

The weight-drag-thrust problem significantly limited the performance of the 141 F-111As. Table 11 compares some of the initial F-111A performance characteristics with the specified performance requirements.

Table 10 does not illustrate the effects of the engine-inlet compatibility problem. Since the stall problem has never been corrected in these aircraft, their operations have been limited to a narrower flight regime than originally planned and their effectiveness has suffered.

---

[1] Coulam, p. 196.

Table 11

F-111A SPECIFIED VERSUS ACTUAL PERFORMANCE[a]

Category	Specified Performance	Actual Performance	Deficiency (Percent)
Take-off Weight	69,122 lbs.	82,500 lbs.	20
Maximum Speed			
High Altitude	2.5 Mach	2.2 Mach	12
Sea Level	1.2 Mach	1.2 Mach	0
Acceleration Time (Mach 0.9 to Mach 2.2)	1.45 min.	4.0 min.	275
Take-off Distance	2,780 ft.	3,550 ft.	28
Ferry Range (nautical miles)	4,180	2,750	34

[a]SOURCE: Coulam, p. 78.

Extensive F-111 program concurrency and pressures to go into production, though not atypical of most aircraft programs of the 1950s and 1960s, were probably aggravated by the Vietnam War. However, the F-111 debut in Southeast Asia proved unsuccessful. The loss of half of the first six F-111As sent to Thailand put an end to F-111A deployment, one month after it began in March 1968. After extensive modifications, the Air Force redeployed F-111As late in 1972. Though they performed well when no problems occurred, many factors including aircraft losses, parts shortages, engine failures, and navigation system malfunctions hindered their effectiveness through 1973.[1]

The Air Force decision to push ahead with F-111A production while unaware of, or in spite of, serious deficiencies constituted a definite tradeoff from the Air Force point of view. The demanding performance requirements and extensive program concurrency resulted in serious aircraft deficiencies, but the Air Force did receive many aircraft relatively quickly. Recalling the relationship, Eq. (9), for effectiveness level, E, the Air Force chose to sacrifice aircraft performance and availability in return for the large quantity of aircraft delivered. Whether or not they understood these implications,

[1]Knaack, p. 232.

the early choice made by Air Force decisionmakers resulted in the rapid delivery of aircraft with only limited utility.

This perspective has broader program implications, too. In many ways, F-111 performance levels desired at the program outset did not appear until production of the F-model; but F-111F production did not begin until 1970, nearly five years after the start of F-111A production. In a large part, the resources devoted to correcting deficiencies in the F-111A, and other models, probably delayed the availability of the F-111F. Also, the F-111F buy only reached about one-third of the planned 219 aircraft because of funding constraints.[1] In retrospect, a more thorough test program, staged decisionmaking, and delayed production commitments, even though delaying initial F-111 availability, might have resulted in more, higher performance aircraft. For Vietnam service, fewer F-111s would have been available early in this alternative acquisition scenario, but the F-111As produced in the actual program provided only minimal service anyway. And, in terms of a long-range need the alternative acquisition strategy probably would have provided an F-111 fleet with far higher effectiveness and future utility.

B. STRUCTURING THE F-111 PROGRAM AS A PAS PROGRAM

The F-111 Program and the Theoretical Model

The high degree of concurrency in the F-111 program makes it difficult to fit the program into the theoretical model. The theoretical model specifies an initial-development phase leading to an initial-production design, which remains frozen until modifications begin. In the actual F-111 program, however, a substantial amount of basic development took place after initial production began and even as full-scale production was underway. This resulted in continual design changes affecting some aircraft through retrofit and others on the production line. As discussed earlier, many of these changes required very fundamental and extensive modifications.

---

[1] Knaack, p. 256.

The narrowed theoretical model focuses on the acquisition phase that leads to modifications and the associated costs. It includes the follow-on development, initial-production, initial-operations, and modifications costs.

As suggested earlier, the F-111 program required production of essentially all the F-111As before subsequent F-111s achieved the desired effectiveness level. Placing the F-111 program in the theoretical-model context requires, then, considering the entire F-111A production run. But, as noted earlier, these first F-111s, about one-fourth of the total produced, have never been completely modified to increase their effectiveness to the desired level. This means that the aggregate effectiveness level of the F-111 fleet has remained below its potential value. This deviates from the constant effectiveness condition in the theoretical model. Though this presents no major analytic problem, it illustrates, as anticipated, that the model does not reproduce all contingencies in the real world.

Accommodating the F-111 Program to a PAS Approach

The PAS approach specifically developed through the narrowed theoretical model incorporates several special features. It maintains the low initial production rate an extended period of time. It increases the length of the low-rate production phase. And, it utilizes early operating data to identify and develop necessary design modifications. In combination, these factors reduce the number of items requiring retrofit and increase the number modified on the production line.

The Air Force implements modifications during the aircraft acquisition process through Engineering Change Proposals (ECPs). Each design change has an ECP number associated with it. The ECP process identifies the nature of the required change, when it originated, retrofit costs, production-line costs, and the numbers of items affected. The ECP data provide the basic information that describes and quantifies the effects of the modifications addressed in this analysis.

In alternative acquisition scenarios, including PAS scenarios, the same ECPs would occur, but they would originate at different

times.[1] When they would originate depends on the underlying mechanisms driving the process of deficiency identification.

I made the key assumption that, during the initial-operating phase, the quantity of cumulative flight hours determines when deficiencies are identified and ECPs are generated. This analysis assumes the same relationship holds across different scenarios. For example, if a given ECP originated at 10,000 cumulative flight hours in the actual program it would do so in each alternative scenario also. For ECPs necessitated by excessive component failure rates, this assumption conforms to the basic concepts of reliability theory.[2] For other ECP types, this assumption appears reasonable though it may lack theoretical and empirical support.

In each scenario, including the actual program, the cumulative flight hours depend on the production and flight rates over time. Thus, the production rate and flight rate profiles in each alternative acquisition scenario determine when individual ECPs would originate.

The analyses of alternative F-111 acquisition scenarios, discussed later, focus on ECPs that originated between 1965 and early 1970 in the actual program. That time period constituted the transition phase, which the narrowed theoretical model specifically addresses, between development and production. However, the theoretical model treats this phase as a time of limited production but, in the actual program, all 141 F-111As were produced during this period. As noted before, this situation complicates the analysis. In spite of this complication, the analysis proceeds to estimate the effects of acquisition parameters on modifications during this period.

---

[1] Note that in a program that used the phased acquisition strategy from the very beginning this might not be entirely true. The phased acquisition approach could, conceivably, improve the early design and development process to the extent that the initial-production design totally avoided many of the design deficiencies that arose in the actual program.

[2] See, for example, Bazovsky, Igor, *Reliability Theory and Practice*, Chapter 21, Prentice-Hall, Inc., New Jersey, 1961.

However, the basic theoretical model alone does not adequately cover costs and benefits of alternative acquisition strategies. Table 12 illustrates the key missing element. The two programs shown would

Table 12

ILLUSTRATIVE COMPARISON OF ACTUAL AND PAS F-111 PROGRAMS

Program	Flight Rate[a]	Production Rate[a]	Date of Last ECP	Number of F-111As Produced
Actual	1	1	3/70	141
Illustrative PAS	2	0.5	3/70	70

[a]Relative to rate in actual F-111 program.

generate the last ECP at about the same date because the higher flight rate and lower production rate, in the PAS program, would generate the same flight hours by March 1970 as the actual program did. Because of the lower production rate, the number of aircraft requiring retrofit would be lower in the PAS program; consequently, total modification costs would be less. But, the important numbers appear in the last column. If we assume that production of the F-111A would discontinue once the March 1970 ECP originated, the PAS program would produce 71 fewer F-111As. As noted before, the A-model suffered severe effectiveness limitations which would have been so costly to correct through retrofit that the Air Force elected to implement them only on subsequent models. Thus, the PAS program would have not only reduced modification costs, but also reduced the number of severely limited F-111As produced.

C. F-111 ANALYSIS METHODOLOGY

Simulation Overview

The analysis of alternative F-111 program scenarios uses a computer simulation model I developed for this application. It retrospectively simulates the activities in the F-111 program related to ECP modifications, from early 1966 through early 1970. Production-rate and flight-rate variables constitute the basic parameters in the simulation model; each set of production-rate and flight-rate variables defines an alternative acquisition program. The production-rate and flight-rate values determine the profile of cumulative flight time. Using the previously postulated relationship between cumulative flight time and ECP generation, the simulation model determines the date when each ECP would have originated in the alternative scenarios. From the ECP-generation date and the production rate the model calculates the number of aircraft retrofit, and the number modified on the production line, through each ECP. It then uses the modification cost data from the actual F-111 program to calculate the retrofit and production-line costs of each ECP. Finally, it calculates how many aircraft of the initial design, corresponding to the limited-effectiveness F-111A, would have been produced in each scenario.

Initial and Full-Scale Production

The period covered by the simulation analysis basically constitutes the initial-production phase. Subsequent production constitutes the full-scale production phase.

Primarily because of data and methodological constraints, this analysis does not estimate how different acquisition scenarios would have affected initial and full-scale production costs. As the C-5A discussion pointed out, though conventional wisdom contends that production costs depend on production rate, no available research has provided a dependable technique for estimating these cost effects.

Though a lower production rate during the initial-production phase might increase associated production costs, neglecting this effect need not detract from the general validity of the results in

this analysis. This occurs for the following reason: To some extent, the full-scale production rates in the actual F-111 program reflected political and budgetary concerns stemming from the serious problems in the program; if a more cautious, lower-rate initial-production phase successfully alleviated many of these problems, full-scale production likely would have been conducted at a higher, more economical rate than in the actual program. Thus, full-scale-production cost reductions in alternative scenarios might have compensated for initial-production cost increases.

Finally, the simulation analysis does not include one potential cost reduction category, thus making estimated cost reductions conservative. This uncalculated saving category depends on the components affected by modifications. For example, assume the fuel pump operates only 20 hours, instead of the desired 100 hours, before requiring maintenance. If the Air Force elects to replace the pump with a longer-lived one after 200 have been installed, then it must buy the original 200 plus the 200 replacement pumps. Under a PAS approach, the number of pumps replaced should decrease, thus decreasing the original investment costs. Due to data unavailability, the simulation model does not estimate the initial production costs of such items replaced through modifications. In the C-5A analysis, the model does estimate these costs because cost data for the original wing are available. The original-wing costs constitute a major cost component in the C-5A case. In the F-111 program, however, the lack of original component cost data and a lack of information on the extent of scrapping make it impossible to estimate the magnitude of costs associated with this activity. Therefore, though these costs would be less in alternative programs that reduced the number of F-111s retrofit, the simulation model could not estimate the potential savings.

Follow-On Development and Initial Operations

In the theoretical model, development that takes place during the initial-production phase is called follow-on development. This development work leads to the changes incorporated during modifications. The concurrent operating experience of initial systems complements and substitutes for a portion of follow-on development.

In Eq. (12) the costs of follow-on development depend directly on the length of the follow-on development phase. Where this relationship applies, follow-on development costs would be large for both very short and very long development phases, and would reach a minimum for medium-length phases.

In the actual program, no available evidence indicates how follow-on development costs would actually vary with the length of the follow-on development phase. However, if these costs do depend primarily on time and, if in alternative scenarios the length of this phase does not differ much from the length in the actual program, we may infer that follow-on development costs would also not differ much from their magnitude in the actual program. In the most important alternative scenarios discussed later, the length of this phase does not differ significantly from its actual value, and the change in follow-on development costs should be insignificant.

Many operating costs during the initial-operations phase depend directly on the number of flight hours accumulated. Air Force planning documents budget operating costs strictly according to cumulative flight hours, without applying different expenditure rates to aircraft flown at significantly different flight rates. This analysis uses the same approach. Thus, the estimated operating costs of five aircraft, each flown ten hours per day, would equal the costs of ten aircraft, each flown five hours per day. Using this approach, the simulation model calculates the initial-operations phase operating costs for each scenario.

Production-Line Modifications

Each modification typically affects subsequent production aircraft on the production line. The date associated with each ECP determines how many aircraft remain to be produced and, therefore, the production-line modification costs of that ECP.

ECP data provide information about production-line modification costs. Usually, an ECP has both a fixed and variable production-line cost associated with it. Under our conservative assumptions the

fixed production-line cost does not vary with the scenario.[1] The variable cost, however, depends on the number of aircraft modified on the production line. Since the number of aircraft modified on the production line in alternative acquisition scenarios usually would exceed the number in the actual program, production-line modification costs in the alternative scenarios generally exceed these costs in the actual program.

Retrofit Modifications

Most, though not all, modifications affect aircraft already produced by implementing changes to them through retrofit. The date associated with each ECP, and the previous production rates, determine how many aircraft require retrofit under the ECP, and the associated retrofit costs.

ECP data provide the necessary information about retrofit costs. ECP retrofits usually have both a fixed and variable cost component. The fixed retrofit costs do not vary with the scenario unless a particular scenario totally eliminates retrofit of certain ECPs. The variable retrofit costs depend on both material and labor quantities required. The ECP data base provides information about both the material costs and contractor labor required for each ECP retrofit.[2] Since alternative acquisition scenarios of interest typically would reduce the number of aircraft requiring retrofit, retrofit costs in the alternative scenarios would usually be less than in the actual program.

Data Used in the Analyses

The simulation analysis requires three basic data elements from the actual F-111 program: ECP costs, production rates, and flight rates.

---

[1] In an actual case, implementing PAS might reduce the fixed costs of production-line modifications. This would occur in a PAS program because less tooling might be in place, or the tooling in place might be "soft," in the sense that it was not designed for a specific, high-rate production task; under both circumstances, changing the tooling to perform a given design modification could be less costly than in a conventional program. Since the model takes no account of this effect, the calculated savings tend to be conservative.

[2] Available data do not provide information about military labor required to perform retrofits.

A previous study at Rand compiled F-111 ECP data.[1] The F-111 System Program Office (SPO) provided the basic ECP data. During the period 1966 through early 1970, the Air Force implemented about 2,000 F-111 ECPs, of which only 134 in the available data base contained both production-line and retrofit cost information. Of these, thirty had data gaps or errors. The remaining 104 ECPs constitute the data base used in this analysis. These 104 ECPs, however, capture 95 percent of the total retrofit expenditures during this time period. Since the alternative scenarios would achieve modification cost savings by simply reducing retrofit expenditures, this sample adequately covers the ECPs this analysis should include.

Retrofit modification costs consist of non-recurring, recurring, and labor costs. The data base provided the recurring and non-recurring retrofit costs for 39 of the 104 ECPs in the sample. The mean ratio of non-recurring to recurring retrofit costs equaled 45.3 for these ECPs. I used this ratio to estimate recurring and non-recurring retrofit costs for the remaining 65 ECPs. A previous study indicated that military labor contributed an additional 16.5 percent to retrofit costs during this period.[2] The simulation model increases calculated retrofit costs by 16.5 percent to account for military labor.

Production-line modification costs consist of non-recurring and recurring costs. The available data, however, provided only total production-line modification expenditures for each ECP. I used these data to develop an estimate of recurring production-line costs by dividing each ECP's production-line cost by the number of aircraft modified. Since this estimate includes both apportioned non-recurring cost as well as actual recurring cost, it provides an upper-bound estimate of recurring cost. In the alternative scenarios of interest, the number of aircraft modified in the production line exceeds the number modified in the actual program. Therefore, this upper-bound estimate leads to conservatively calculated cost savings.

---

[1] Unpublished Rand research; see Appendix D for more details.

[2] Unpublished Rand research.

Table 13 presents the number of F-111s accepted annually and cumulative flight hours. The acceptance rate provides a reasonable proxy for the production rate. The model incorporates this rate on a quarterly basis. I used the quarterly production rate and the quarterly flight hours to derive a quarterly flight rate per aircraft. The model contains this rate as the average flight rate, per quarter, in the actual program.

To estimate initial-operations costs the simulation model also requires operating-cost data. The F-111 operating and maintenance

Table 13

F-111 PRODUCTION AND FLIGHT DATA[a]

Year End	Aircraft Produced During Year	Cumulative Aircraft	Annual Flight Test Hours	Annual Operational Flight Hours	Cumulative Flight Hours
1964	1	1	0	0	0
1965	9	10	460	0	460
1966	12	22	1,700	0	2,160
1967	22	44	2,829	1,879	6,868
1968	68	112	2,371	11,159	20,398
1969	118	230	2,462	29,681	52,541
1970	96	326	1,851	14,966	69,358
1971	70	396	2,257	59,753	131,368
1972	110	506	1,934	103,234	236,536
1973	34	540	1,207	118,614	356,357

[a]Aircraft delivery schedule is from *Acceptance Rates and Tooling Capacity for Selected Military Aircraft*, OASD (PA&E), October 1974. Flight data are from a personal communication, John Schank, Rand Washington Office, November 1, 1977.

costs that depend on flight time were as follows:

- Total maintenance cost = \$1,263/flight hour
- Replenishment spares = \$ 925/flight hour
- Fuel and oil = \$ 264/flight hour
- Total variable cost = \$2,452/flight hour.[1]

The time-dependent O&M costs in each scenario then equal the product of cumulative flight hours and \$2,452 per flight hour.

Scenario Variables

Production rates and flight rates define each scenario analyzed through the simulation model. Basically, each scenario can be specified in terms of its production and flight rate, relative to the rates in the actual program, on a quarter-by-quarter basis.

In addition, the model permits a subset of aircraft to have flight rates higher than the average value. Actual programs sometimes use this approach to acquire intensive flight experience rapidly on a group of aircraft. By doing so, these aircraft often reveal problems well before the majority of the inventory encounters them. This tactic is usually called a *lead-the-fleet* program. The simulation model accommodates two such approaches: (1) a fixed *number* of initial aircraft constitute the lead-the-fleet group, or (2) a fixed *proportion* of all production aircraft constitute the lead-the-fleet group.

Thus, several variables characterize each scenario. First, the production rate indicates the number of aircraft produced per quarter. Second, the average flight rate indicates how many hours the majority of aircraft fly each quarter. Third, the initial number or proportion indicates how many aircraft enter the high flight-rate, lead-the-fleet group. And fourth, the lead-the-fleet flight rate indicates the flight rate of aircraft in the lead-the-fleet group.

---

[1]From "USAF Cost and Planning Factors," *Air Force Manual 172-3*, 1970 and adjusted to 1975 price levels.

Simulation Model

Figure 12 presents an overview of the simulation model. The model is a Fortran program, and it calculates ECP costs for each scenario specified by the model inputs.

The first step consists of identifying the characteristics of specific scenarios. The input information contains initial conditions of the scenario including the number of aircraft in the inventory, the number of aircraft in the lead-the-fleet group, and the flight hours already accumulated by the two groups of aircraft. The input data also specify subsequent conditions including quarterly flight rate, quarterly production rate, and the proportion of aircraft joining the lead-the-fleet group. The input data indicate production and flight rates relative to those in the actual program; for example, the model would simulate the actual program whenever the input consisted of a series of "1s" for the relative production and flight rates

The simulation then uses the initial conditions and the first-quarter variable values to advance the program through its first quarter. It calculates the number of aircraft added during the quarter and the average flight rate, both for the regular aircraft and the lead-the-fleet group.

Third, the simulation model calculates program characteristics at the end of the current quarter. Specifically, it calculates the number of aircraft in the regular and lead-the-fleet group, the cumulative flight time for both groups, and the total cumulative flight time.

Next, it determines which ECPs would originate during the current quarter. The model uses the assumption, described earlier, that cumulative flight time drives the ECP generation process. It compares the current cumulative flight hours in the scenario with the corresponding value for ECPs from the actual program; if the scenario flight hours exceed, for the first time, the value for a specific ECP, the model indicates that ECP originates during the most recent quarter.

Fifth, the model checks to see if all ECPs have been generated. If not, the simulation advances one quarter and repeats the above steps; if they have, the model enters the output calculation stage.

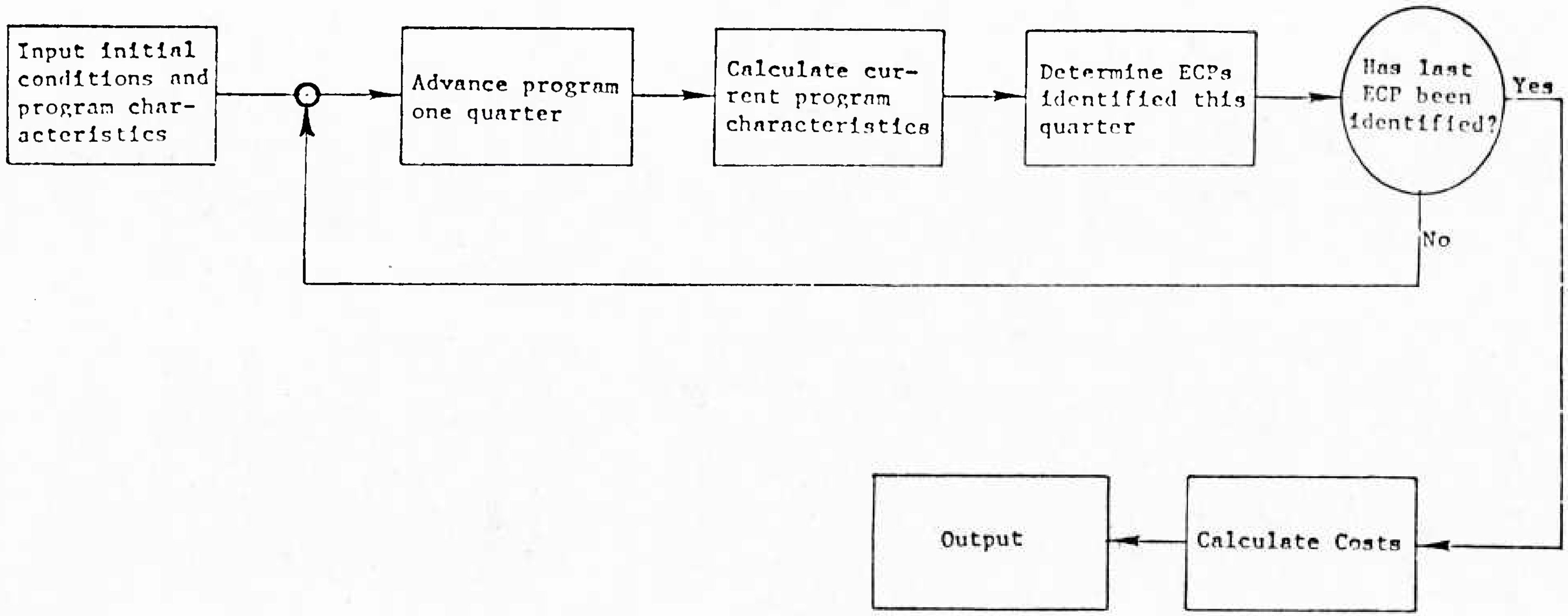


Fig. 12--F-111 simulation model schematic

The simulation model calculates when each ECP would originate under alternative scenarios and calculates the numbers of aircraft modified on the production line and through retrofit and the associated costs.

The calculations primarily determine the modification costs. The number of aircraft retrofit by each ECP, times the recurring retrofit cost, plus non-recurring retrofit cost gives the retrofit cost for each ECP.[1] The sum of these costs gives the total retrofit cost for the scenario. The recurring production-line modification cost for each ECP, times the number of aircraft modified on the production-line gives the production-line modification cost of each ECP. The sum across all ECPs gives the total production-line modification cost. Summing these two modification cost components produces the total modification cost for the scenario. The model also calculates the distribution of flight times on the aircraft and the number of aircraft produced over time.

Finally, the model outputs the results in the form of a computer printout. It lists the quarterly distribution of aircraft by flight time. And, for each ECP, it presents the generation date, retrofit costs, production-line costs, and the numbers of aircraft affected through retrofit and on the production-line. Finally, the output presents the complete retrofit, production-line, and total modification costs.

D. SIMULATION ANALYSES AND RESULTS

Objectives

The simulation model indicates how production rate, flight rate, and lead-the-fleet program characteristics affect modification costs. Variations in one parameter at a time reveal how individual parameters affect modification costs. Since extreme variations in one parameter may present serious problems, analyses of individual parameter effects help identify both reasonable and effective values. For example, though modification costs may fall with increasing flight rates, the Air Force may not have the capability to support very high flight rates. The analyses reveal whether more moderate, supportable flight rates would produce acceptable cost savings. The model also provides information about simultaneous variations in several program parameters.

---

[1] The model also adds 16.5 percent to account for military labor costs.

The acquisition scenarios of special interest include reduced initial production rates, increased average flight rates, and a lead-the-fleet program. Such program parameters agree with the acquisition strategy trends discussed earlier and with the strategy I have called PAS. Since there are an infinite number of possible combinations of program parameters consistent with PAS, we need some technique for selecting the most promising combinations. The analyses of individual parameters, discussed in the previous paragraph, provide one approach for defining reasonable PAS scenarios.

In general, the various scenarios have the objective of reducing modification costs by shifting modifications from retrofit to the production-line. Usually, unit retrofit costs exceed unit production-line modification costs, at least by the cost of labor required to remove the original item. Thus, reducing the amount of retrofit reduces total modification costs. The scenarios this analysis focuses on employ reduced production rates, higher flight rates, and lead-the-fleet programs to increase flight experience while reducing the number of aircraft requiring retrofit.

The simulation analyses also address one effectiveness component. As described earlier, the entire F-111A production run suffers from effectiveness limitations which are too costly to correct through retrofit. The alternative program scenarios would produce different numbers of aircraft during the early production phase. If we assume that F-111A production would cease in each program as soon as a given set of modifications began, then we can calculate how many effectiveness-constrained F-111As each program would produce. Programs that decrease the number of F-111As would increase overall fleet effectiveness.

Base Case--The Actual F-111 Program

This analysis treats the actual F-111 program as the reference, or base, case. The production rate starts at three aircraft per quarter, in January 1966; it reaches 30 aircraft per quarter in 1969, and then drops off to about 18 per quarter in 1971. The average flight rate equals about 27 hours per quarter for each aircraft in

1966; it rises to 47 hours per quarter in 1969 and drops back to 15 hours per quarter in 1970; and, in 1971 it climbs back up to 43 hours per quarter. The base case includes no lead-the-fleet program.

The sample ECPs cost $273 million to implement in the actual program. ECP retrofits contribute $110.5 million and production-line modifications add $162.4 million.

In the ideal case the acquisition strategy would eliminate retrofit entirely. In this case, all modifications would occur on the production line only and modification costs would decrease to $203 million. Thus, such a scenario would reduce modification costs $70 million, about the cost of seven F-111s. This figure, $70 million, represents the maximum savings an acquisition strategy could achieve and all savings in the following cases are presented relative to this maximum potential amount.

In the base case, the program produces 141 F-111As through the second quarter of 1969. The following discussions indicate how many effectiveness-limited F-111As would be produced in the alternative cases described.

Production-Rate Effects

Reducing the production rate, while keeping other program variables unchanged, reduces the number of aircraft requiring retrofit. This happens as a result of the relationship between cumulative flight hours and ECP generation. The effect reduces costs only modestly, however, because of two factors. First, the average flight rate increases substantially over time so that, as time passes, each aircraft contributes a growing amount of flight hours to the total. Second, at low production rates, however, production must continue for relatively long periods to build up fleet size enough to accumulate large amounts of flight hours. As fleet size increases so do the number of aircraft requiring retrofit and their associated retrofit costs. These two opposing factors tend to minimize production rate effects on modification costs.

Figure 13 shows production rate effect on modification costs.

The abscissa indicates the production rate relative to the rate in the actual F-111 program.[1] One curve shows modification cost savings, as a percent of the potential $70 million savings. This curve indicates that savings increase nearly linearly as production rate decreases; each 10 percent decrease in production rate reduces modification costs about 2.5 percent of the maximum amount possible. At one-half the actual production rate, savings equal about $9 million, or about 13 percent of the maximum amount possible.

Fig. 13 also shows how production rate affects the quantity of F-111As produced. Using this quantity as a measure of effectiveness reductions in the F-111 program, higher effectiveness results when small quantities of F-111As are produced. The production rate has little effect on F-111A quantities until it falls below half the actual rate. When it reaches two-tenths the actual rate, the number of F-111As declines to 76, only about half the number in the actual program.

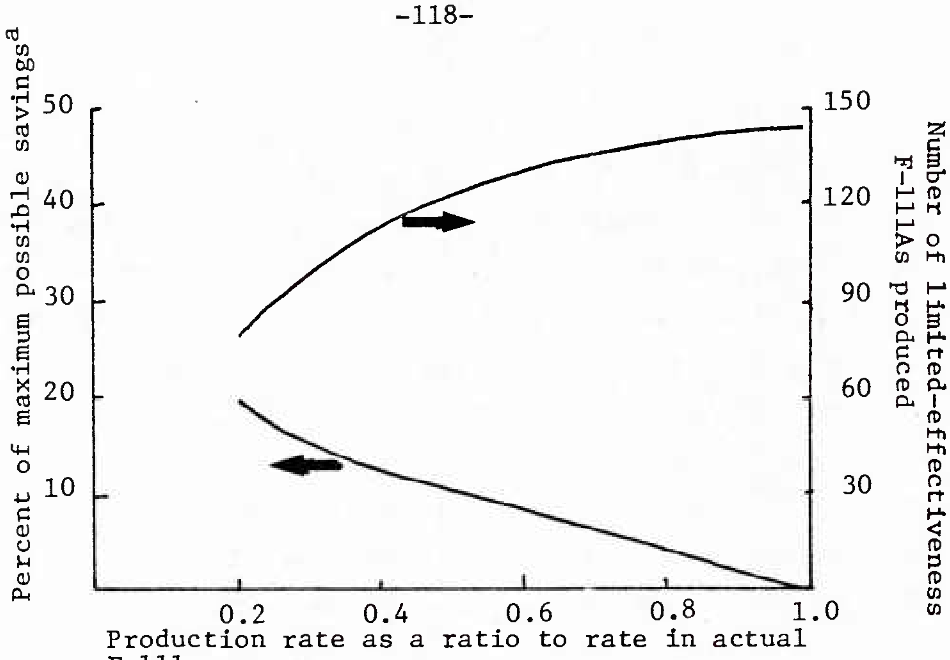
On the whole, production rate variations alone do not cause significant program improvements. However, production rates lower than 30 percent of the actual rate begin to reduce modification costs a reasonable amount, and reduce F-111A quantities significantly. Such low production rates, however, may cause unacceptable production stretchouts.

Flight Rate Effects

Increasing the flight rate, keeping other program variables unchanged, decreases retrofit costs. Retrofit quantities and costs decrease through a series of steps. First, higher flight rates reduce the number of aircraft required to generate a given number of cumulative flight hours. Second, the model uses the assumption that ECP

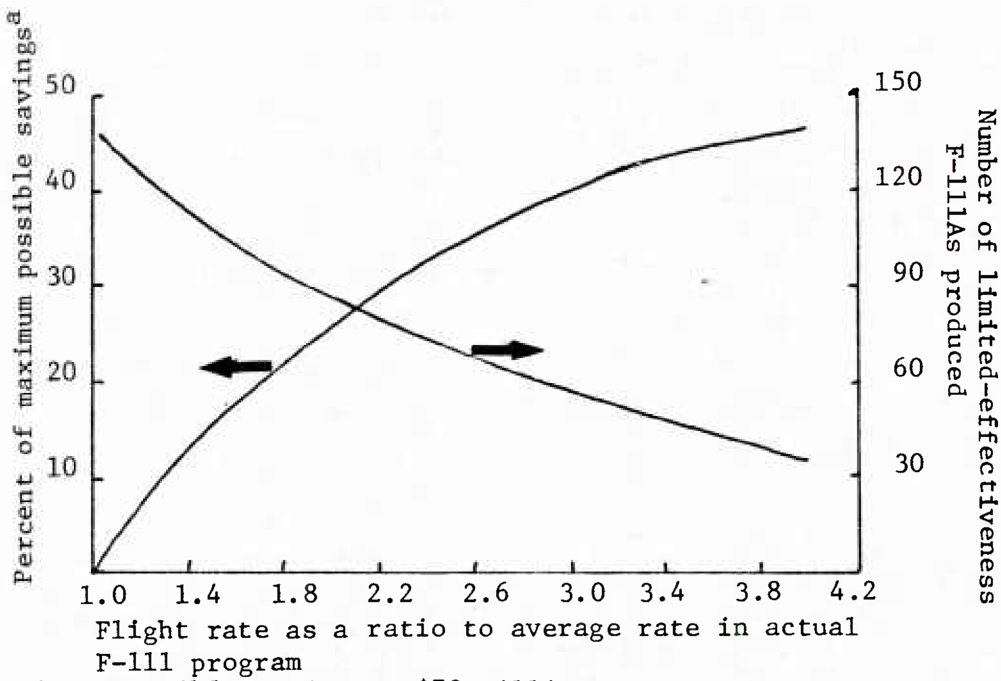
---

[1] Note that a relative rate of two-tenths appears to be about the lower bound for a viable program, so the analysis does not consider lower production rates. Note, also, that the simulation analysis makes the conservative assumption that each scenario incurs the complete fixed retrofit costs regardless of the number of aircraft retrofit. In reality, the Air Force would probably elect to forgo certain retrofit modifications if their fixed costs were excessive for the number of aircraft retrofit. In this case the savings shown in Fig. 13 would increase and approach 100 percent of the maximum possible savings.



[a]Maximum possible savings = $70 million.

Fig. 13—F-111 production rate effects, holding all other program characteristics at actual program values



[a]Maximum possible savings = $70 million

Fig. 14—F-111 flight rate effects, holding all other program characteristics at actual program values

generation depends directly on cumulative flight hours. Finally, the number of aircraft already produced when an ECP originates determines how many aircraft that ECP retrofits. Therefore, higher flight rates decrease the number of aircraft retrofit through ECPs.

Figure 14 shows the effect of relative flight rate on modification cost savings. Up to twice the actual flight rate, savings increase rapidly, almost linearly with flight rate. Thereafter, the rate of increase falls and savings hardly increase at all for flight rates greater than three times the actual program values. Up to twice the actual flight rate, savings increase about 3 percent of the maximum possible amount for every 10 percent increase in flight rate. At twice the actual flight rate, savings equal about 30 percent of the maximum possible, or $21 million; for higher flight rates, savings increase, but to only about 40 percent of the maximum possible, at five times the actual flight rate.

Figure 14 also shows how the relative flight rate affects the number of F-111As produced. Increasing flight rate affects the number of F-111As in a pattern similar to its effects on modification costs. Up to about twice the actual flight rate, the number of F-111As decreases nearly linearly with flight rate. Thereafter, it continues to decrease but at an increasingly smaller rate. At about four times the actual flight rate, the number of F-111As levels out at about 36 aircraft.

Flight rate has a fairly significant effect on program outcomes. Increases in aircraft flight rate reduce the number of aircraft requiring retrofit and reduce modification costs. Higher flight rates also increase fleet effectiveness by decreasing the number of effectiveness-limited F-111As built. Flight rate has the most dramatic effect for values up to about twice the actual program rates. If the Air Force could have supported it, an increase in initial flight rates would have reduced F-111 modification costs and increased fleet effectiveness.

Lead-the-Fleet Effects

The Air Force could fly only a subset of aircraft at a high flight rate as one way to accumulate flight time rapidly. This approach constitutes a *lead-the-fleet* program. Such an approach would place fewer demands on the support system than an attempt to fly all aircraft at a high rate; for this reason, a lead-the-fleet program has implementation advantages.

This research considers two lead-the-fleet program types. One type flies a fixed set of aircraft at a high rate. The other puts a constant fraction of all production aircraft in the lead-the-fleet group. In the second type, the size of the lead-the-fleet group increases over time. In this second approach, though the eventual number of aircraft in the lead-the-fleet group may get fairly large, the support system should have time to adjust to it.

Table 14 shows the effects of various illustrative lead-the-fleet programs. The first two results illustrate the first type of program: ten initial aircraft constitute the lead-the-fleet group. With a flight rate twice the actual program value, modification costs fall 13 percent of the maximum possible amount. At a flight rate four times the actual, savings increase to 33 percent of the maximum. The next four cases illustrate the second program type: a fixed proportion of aircraft enter the lead-the-fleet group. The first two cases show the results when the flight rate equals twice the actual rate. With 20 percent of all aircraft in the lead-the-fleet group, savings are negligible; with 40 percent in the high-rate group savings equal 15 percent of the maximum amount. The next two cases show the results with the flight rate four times the actual rate. With 20 percent of the aircraft in the lead-the-fleet group, savings equal about 15 percent of the maximum amount possible; with 40 percent in the lead-the-fleet group savings reach 31 percent of the maximum. At both flight rates, savings did not reach significant levels until 30 to 40 percent of the aircraft joined the high-rate group. Other results, not shown here, indicate that savings tend to level off at higher proportions of aircraft in the lead-the-fleet group.

Thus, in terms of modification costs, modest applications of

Table 14

F-111 LEAD-THE-FLEET EFFECTS

Lead-the-Fleet Program				
Initial Lead-the-Fleet Aircraft	Proportion of Production Lead-the-Fleet Aircraft	Lead-the-Fleet Flight Rate[a]	Modification Cost Savings, % of Maximum Possible[b]	Number of F-111As Produced[c]
10	-	2	13	141
10	-	4	33	110
0	0.2	2	~0	141
	0.4	2	15	110
0	0.2	4	15	110
	0.4	4	31	87

[a]Relative to flight rate in actual program.

[b]Maximum possible savings = $70 million.

[c]141 F-111As produced in actual program.

either lead-the-fleet tactic could decrease modification costs effectively. Flight rates between two and four times the actual rates appear most acceptable and effective. As few as ten initial aircraft, or 30 to 40 percent of subsequent aircraft, could reduce modification costs between about 15 and 30 percent of the maximum amount possible.

The lead-the-fleet cases described here have little effect on the number of F-111As produced. Table 14 shows that the strategy using 10 aircraft in the lead-the-fleet group reduces F-111As only when the flight rate reaches four times the actual value. In the approach with a constant proportion in the high-rate group, the effect has significance, again, only when flight rate equals four times the actual value. In the extreme case, where 40 percent of all aircraft have a flight rate four times the actual program value, a significant effect occurs, with 54 fewer F-111As produced.

In summary, the lead-the-fleet strategy offers reasonable benefits when high flight rates are used. Since only a subset of the fleet flies at high rates, these rates may be supportable. The aircraft in

the lead-the-fleet group would certainly require special support and attention. Savings from about 15 to 30 percent of the maximum appear reasonable. Also, overall effectiveness would increase due to reduced production of F-111As. However, this effect seems fairly minor except in extreme cases.

<u>Representative PAS Case</u>

An acquisition scenario could combine variations in several of the individual program variables described earlier. Such an approach permits obtaining the benefits of varying each variable while minimizing negative effects, such as program stretchout. An unlimited number of potential program combinations exist, but the prior explorations of individual variables help narrow the choice to a range of reasonable and effective combinations. With appropriate choices of variables, such combinations exemplify typical phased acquisition strategies.

Without optimizing the selection process, I have chosen, as a representative PAS program, a scenario described in part by the following characteristics:

- o Five initial aircraft and half the production aircraft, through 1971, enter a lead-the-fleet group.
- o Production rate equals three-per-quarter through the end of 1969 (about one-fourth the overall average rate during this period in the actual program) and increases to the actual rate by 1971.

The scenarios also require specification of flight rates for completeness. The following table shows the results for two different sets of flight rates.

Table 15

REPRESENTATIVE PAS PROGRAM RESULTS

Basic Flight Rate[a]	Lead-the-Fleet Flight Rate	Savings, % of Maximum Possible[b]	Number of F-111As
1[c]	2[c]	38	47
2[c]	4[c]	41	27

[a]Basic flight rate applies to all aircraft not in the lead-the-fleet group.

[b]Estimated maximum possible savings = $70 million.

[c]Flight rates are expressed as multiples of the rates in the actual program.

These results indicate the significant benefits of combining several parameter variations into one strategy. In the first of the two cases, the basic flight rate does not differ from the actual program rate, and the lead-the-fleet rate equals only twice the actual rate; yet, savings reach nearly 40 percent of the maximum amount possible. This amount exceeds savings from each previous case, except those where individual parameters varied an extreme amount. The second case in Table 15 provides assurance that PAS scenarios need not incorporate extreme program variations to reduce costs significantly. This case doubles all flight rates, yet increases savings from the first case by only 3 percent of the maximum amount possible.

Table 15 also shows one measure of how PAS varies the effectiveness-level, the number of F-111As produced. In both cases, PAS significantly reduces the number of effectiveness-limited-F-111As than the actual program did. The second case, through its higher flight rates, reduces the number of F-111As by an additional twenty aircraft. The magnitude of these reductions makes them a very important factor in assessing the value of applying PAS in a program such as the F-111.

In addition to modification costs and effectiveness levels, operating costs would vary from one scenario to the next. Initial operating costs constitute one of the cost components included in the theoretical model, developed in Section III. Information from both the actual F-111 program and the scenarios here permits a first estimate of scenario effects on initial operating costs. The Air Force budgets many O&M expenditures as a function of cumulative flight hours. Aggregate O&M costs, then, depend on cumulative flight hours. A previous section presents the F-111 O&M costs that depend on flight hours. Multiplying the variable cost by the cumulative flight hours gives an estimate of O&M costs in each scenario. Table 16 compares the flight hours and shows the difference between O&M costs in the actual F-111 program and the representative PAS program, described above, and with flight rates as shown by the first case in Table 15.

In this comparison, the annual O&M costs in the PAS scenario exceed those in the actual program for only the first two years. For the next three years the reverse situation exists. After peaking in the fourth year, the annual difference tends to decrease. These results suggest a PAS approach might change the distribution of O&M costs over time. Initial, small cost increases give way to larger cost savings. However, over the lifetime of a system the cumulative variable O&M costs should not vary from scenario to scenario if aircraft accrue equal numbers of flight hours.

Table 16

FLIGHT HOURS AND O&M COST COMPARISONS

Year End	Cumulative Flight Hours		O&M Cost Difference (PAS Minus Actual Program Cost)	
	PAS Program	Actual Program	Annual	Cumulative
1966	3,543	2,160	\$ 3.4M	\$ 3.4M
1967	9,875	6,868	\$ 4.0M	\$ 7.4M
1968	20,747	20,398	-\$ 6.5M	\$ 0.9M
1969	35,895	52,541	-\$41.7M	-\$40.8M
1970	43,880	69,358	-\$21.7M	-\$62.5M

E. CASE STUDY SUMMARY

Characteristics of Actual Program

The F-111 program required significant technological advances in several areas, attempted to develop a multi-mission system, and made poor use of the acquisition strategy to resolve technical uncertainties. The design incorporated unproven engine, structural, and avionics components. In spite of their recognition of the aircraft design challenges, planners underestimated the difficulty of developing the requisite technologies. The acquisition program incorporated considerable concurrency between development and production, and the Air Force contracted for production before receiving the initial flight test data generated by the contractor. These data had provided warnings, unknown to the Air Force, of one of the major problems to later plague the F-111 design--engine-inlet incompatibilities.

This acquisition approach led to rapid initial development of a design that required extensive subsequent modifications and delivered severely limited effectiveness. First flight occurred only about two years after program go-ahead. Though serious design problems became apparent during the early production years, the production program continued at an increasing pace. The program appeared to ineffectively match testing with program decisions since crucial fatigue test failures occurred after the high-rate production decision. The F-111 has required very extensive costly design modifications. In addition, the first quarter of the production aircraft would have required such expensive retrofits to improve their effectiveness to acceptable levels that the Air Force has accepted their severe effectiveness limitations instead.

Expectations Based on Research Findings

If any recent Air Force program has approached the archetype about which past research has cautioned us, it would have to be the F-111 program. Past research has predicted cost growth, design deficiencies, and schedule delays in programs such as the F-111, which required substantial technological advance within a highly concurrent acquisition

strategy without suitable testing and use of test data.

The theoretical model in this dissertation would categorize the F-111 program as an appropriate candidate for the PAS approach. The aircraft incorporated more than 2,000 design modifications--including those to enhance performance as well as meet design goals--during its early production years; total modifications costs exceeded one billion dollars. Retrofit costs constituted a few hundred million dollars and, therefore, offered large saving potential. As with the C-5A analysis, we could not estimate how much suitable planning could have reduced the costs of stretching out the low-rate production phase. Note, however, that the planned production quantity varied dramatically as follows:

- 1,726 aircraft at program go-ahead,
- 2,411 aircraft prior to flight test,
- 1,372 aircraft at production contract agreement, and
- 565 aircraft planned as of January 1976.

Though these data provide no direct information on time-dependent cost factors, we could infer that the contractor had planned for a much larger production quantity than the actual buy required. Initial tooling and staffing probably reflected the large expected production rates that never materialized. Under a PAS approach, program managers would have *planned a less rapid production rate increase*, thereby minimizing stretchout costs that were incurred fortuitously in the actual program. Furthermore, the actual program probably faced high costs, which a PAS approach would have avoided, due to schedule compression.

This research also has suggested PAS would have offered effectiveness increases. Though PAS would have delayed high-rate delivery, we would expect it to improve aircraft effectiveness.

The F-111 program appeared to be a good candidate to benefit from PAS. The design involved major and widespread design uncertainties; the program had considerable development-production concurrency; the schedule resulted in crucial test data availability only after major decision points; and, the interaction between the Air Force and contractor appeared inadequate.

PAS Effects

This analysis has investigated the effects of a PAS approach on the F-111 program by investigating variations in several decision variables separately and in combination. The decision variables included production rate, flight rate, and lead-the-fleet program characteristics. Though individual variables did affect program costs, they appeared most effective and feasible when varied simultaneously as in a PAS scenario. This section defined a representative PAS case as follows:

- o Five initial and half the F-111s produced through 1971 enter the lead-the-fleet group.
- o Lead-the-fleet flight rate equals twice the average in the actual F-111 program.
- o All other aircraft fly at the program average rate in the actual F-111 program.
- o Production rate equals 12 aircraft per year through 1969 and increases to the actual program rate thereafter.

This PAS scenario led to the following results:

- o Costs decreased nearly $30 million.
- o Low-rate production lasted about an additional two years.
- o Overall effectiveness increased substantially.

The cost reductions, though several million dollars, appeared smaller than expected. The longer low-rate production phase would have decreased the initial inventory size. The most significant benefit appeared to be a large effectiveness increase which relates, in turn, to the modest cost reduction. As noted earlier, the Air Force accepted 141 limited-effectiveness F-111s in lieu of making excessive expenditures to correct their deficiencies. If they had been retrofit, this analysis would have shown a much larger cost reduction. Instead, it indicated that the number of limited-effectiveness F-111s would have decreased by about one hundred.

This analysis has shown PAS could have increased the F-111 fleet effectiveness level substantially. PAS would have reduced costs, but

this benefit would have been secondary to the effectiveness increase. PAS would have delayed, however, the growth in the F-111 fleet.

VII. CASE STUDY OF THE F-15

A. F-15 PROGRAM DESCRIPTION

Program Overview

The F-15 fighter represents the first major Air Force aircraft program after the disappointing experiences of the 1960s. In many ways, the program has taken advantage of lessons learned from earlier programs, but, in other ways, it has failed to heed warnings from the past. During the early years of the program, the Packard initiatives went into effect so the program partially reflects policies established by these initiatives. Figure 15 illustrates some major events in the F-15 program.

McDonnell-Douglas received the F-15 airframe contract in December 1969. The contract had a structure similar to Total Package Procurement but incorporated a set of milestones. The milestones required the contractor to demonstrate satisfactory performance at key decision points; if unsatisfied, the Air Force retained the option of delaying commitments to the program. The initial contract required the contractor to conduct necessary engineering and development, acquire production tooling, and produce twenty preproduction aircraft for testing.

In several ways, the F-15 program has taken advantage of a more conservative approach than its predecessors. The procurement approach has instituted increased Air Force control over program decisionmaking.[1] The early design process required assessments of design effects on eventual logistic support requirements to control support costs.[2] The program manager, Major General Bellis, had a mandate to desophisticate the aircraft and establish a conservative design requiring minimum modifications; Bellis stated at one point, "It is very interesting to note that the contract with McDonnell-Douglas now is over fifteen months old and the net result of our engineering change activity to

---

[1] Whittaker, Philip, "New Approaches in Major Weapon System Contracting," *Defense Industry Bulletin*, March 1970, p. 26.

[2] Whittaker, p. 28.

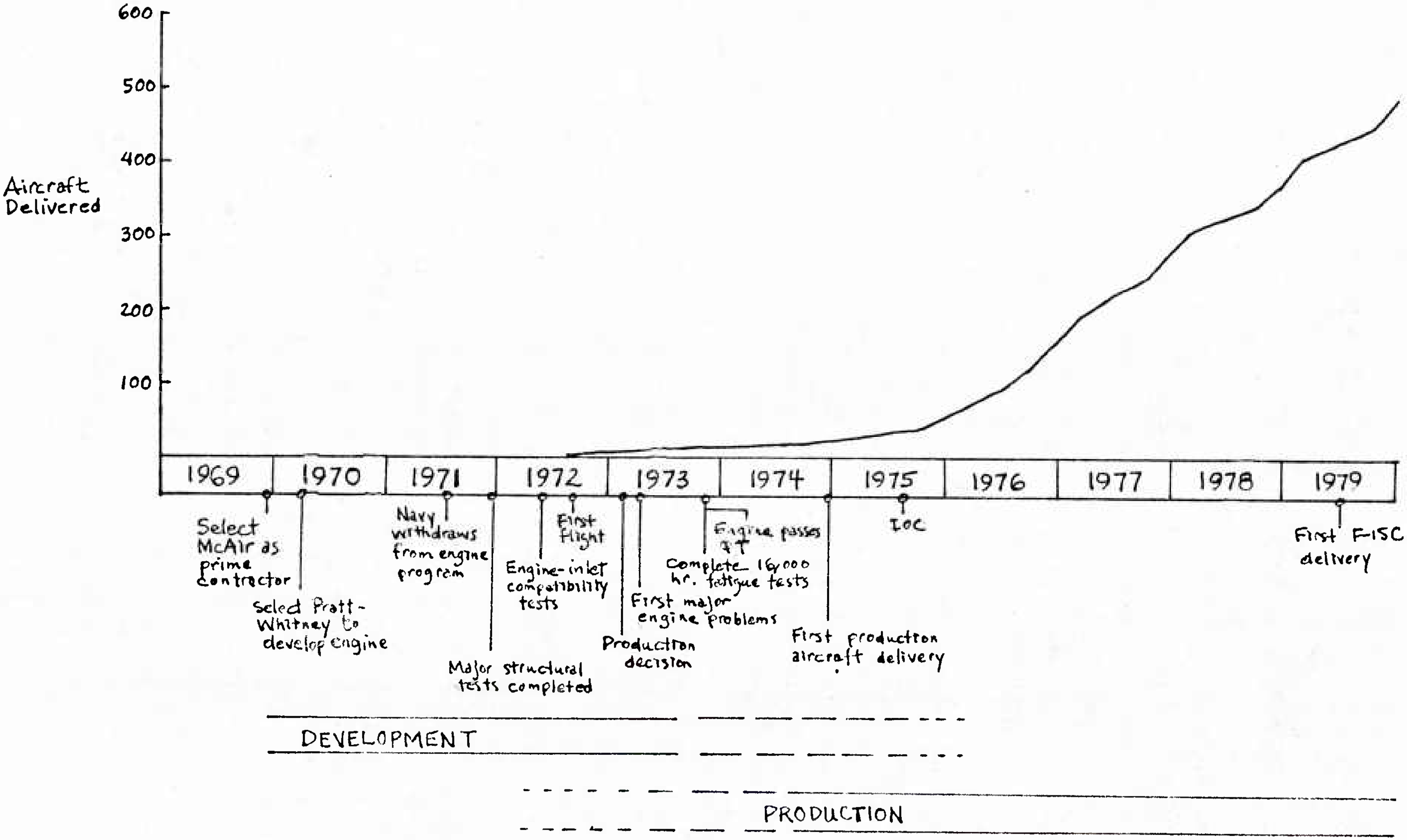


Fig. 15—F-15 program history

date has been a net dollar reduction."[1] By early 1974 the Air Force had approved only 35 design changes, of which only two were not on the initial production aircraft.[2]

Responding to earlier lessons, the F-15 program has emphasized testing. By early 1973, wind-tunnel test hours reached nearly three times the quantity in the entire F-4 program.[3] Largely as a result of F-111 experiences, these tests intensively explored potential engine-inlet compatibility problems. Late in 1973, the airframe had completed fatigue tests equivalent to four lifetimes.[4] In addition, the flight test program progressed at a faster pace than in any previous jet aircraft development.[5]

Information from the test programs frequently resulted in timely design changes. Fatigue test failures led to wing spar modifications. Flight tests elicited the need for changes in the variable-geometry engine inlet ramp sensitivity, control stick forces, and flight control system.[6]

In other ways, however, the program has involved considerable risk. The engine, the F100, represents a significant technological advance. Though a new, advanced design, the actual engine development award did not occur until March 1970, three months after the airframe contract. The engine did not pass its required Qualification Test (QT) until October 1973, when ten preproduction aircraft had already been delivered. Though the Air Force minimized avionics requirements in some areas, contractor selection derived from only paper studies.[7] Furthermore, some components, such as the radar, represented significant technological advances and their development overlapped airframe development. In addition, the Avionics Intermediate Shop (AIS)--sophisticated avionics test equipment--was developed before tests had

---

[1] *Government Executive*, June 1971, p. 36.

[2] *Aviation Week & Space Technology*, March 1, 1974, p. 53.

[3] *Aviation Week & Space Technology*, March 9, 1973, p. 14.

[4] *Aviation Week & Space Technology*, October 29, 1973, p. 49.

[5] *Aviation Week & Space Technology*, November 21, 1973, p. 11.

[6] *Aviation Week & Space Technology*, October 29, 1973, p. 50.

[7] *Aviation Week & Space Technology*, October 29, 1973, p. 52.

proven the avionics design and the AIS subsequently required extensive modifications when avionics redesign took place.[1]

In one other component the F-15 program has allowed necessary flexibility. The initial F-15 design included an unproven gun, the GAU-7A; however, the design also permitted use of the proven M-61 gun. When cost, weight, and performance problems plagued the GAU-7A program the Air Force dropped it, in favor of the M-61, in the middle of 1975.[2]

Program Problems

The F100 engine has caused substantial problems during the first few years of the F-15 program. Early fuel flow regulator and afterburner control problems showed up in flight tests.[3] The engine failed its first QT in February 1973. Explosions and less severe failures aborted several subsequent engine tests. The engine successfully passed its QT in October 1973.[4] However, flight-test and operational aircraft experienced serious stall problems, electronic control system failures, and turbine blade cracking.[5] These problems have necessitated many engine modifications up until about 1979, requiring expenditures of over $660 million.[6]

Partially because of early engine development problems, the Navy dropped out of what began as a joint engine development effort. Early plans had included a Navy F401 as a counterpart to the Air Force F100. The engines were to share several components and distribute development costs among a much larger number of engines, thus reducing individual engine costs. The Navy pullout caused about a $523 million increase in F100 program costs.[7]

---

[1] *Aviation Week & Space Technology,* December 15, 1975, p. 23.

[2] *International Defense Review,* June 1975, p. 361-371.

[3] *Aviation Week & Space Technology,* April 19, 1973, p. 17.

[4] *Flight International,* January 23, 1975, pp. 101-105.

[5] *Aviation Week & Space Technology,* May 12, 1975, p. 18.

[6] *DMS Market Intelligence Report,* Greenwich, Connecticut, 1979.

[7] *Flight International,* January 23, 1975, pp. 101-105.

The Navy withdrawal and other factors have caused considerable cost growth in the F-15 program. The initial estimate places total program cost at nearly $6 billion, in 1970 dollars. The initial estimate includes an additional $1.4 billion to cover inflation. Recent estimates place total program cost at $14.2 billion, in then-year dollars, nearly twice the original estimate. Schedule changes, through reduced production rates, have increased costs $835 million; engineering changes have added $252 million; and, all other changes except inflation have added $463 million. Unanticipated inflation has added the major cost increment, $5.3 billion. The factors other than inflation have increased program costs 21 percent, while inflation has had the largest impact--about 72 percent.[1] Though some controversy exists over the attribution of cost growth to those different factors, the very high inflation rates of the mid-1970s undoubtedly caused the largest single element of F-15 program cost growth.

Largely because of cost growth, F-15 production rates have never reached their anticipated levels. To minimize annual expenditures, Congress frequently reduces annual production quantities. In turn, since the production line then operates at less than optimum production rates, production costs increase. This delays program expenditures and aircraft availability, and increases total program cost. As noted above, F-15 cost increases of $835 million have been attributed to this effect.

One of the few performance short-falls of the F-15 has been a diminished combat radius. The solution has consisted of the addition of internal fuel capacity plus provision for conformal, external fuel tanks. This program, known as the PEP-2000 and FAST Pack modifications has increased combat radius 100 percent at a cost of about $500,000 per aircraft, for the increased fuel capacity alone.[2] The necessary design changes went into the 404th and subsequent production aircraft; the extent of the changes led to a model designation change from F-15A and F-15B to the F-15C and F-15D.[3] Though these changes largely compensated for performance shortfalls,

---

[1] *Selected Acquisition Report*, March 31, 1980.

[2] *Interavia*, December 1978, pp. 1178-1179.

[3] The F-15A is the original single-seat version; the F-15B, also known earlier as the TF-15, is the two-seat trainer. The F-15C is the current single-seat version and the F-15D is the current two-seat version.

they also increased F-15 capacity and growth potentials beyond original specifications.

Largely because of higher than expected failure rates and inadequate spares, the F-15 has had a disappointing operational experience. Late in the 1970s, the F-15 operational readiness rate has hovered around 50 percent, falling as low as 40 percent during several months. This rate falls about 30 percent short of the target rate. To keep aircraft operating, maintenance personnel have frequently removed parts from other aircraft. Across all Air Force aircraft the cannibalization rate was about 0.04 per flight hour, while it reached 0.3 per flight hour for the F-15 during 1979.[1]

Unique Features of the F-15 Program

The F-15 program provides some information about the effects of an acquisition strategy designed more conservatively than those of programs from the 1960s. The acquisition initiatives and policies from the early 1970s have influenced the structure of the F-15 program. Their influence, however, has been incomplete since many policies originated only after initial program planning took place. Much evidence indicates that the airframe development followed a conservative design philosophy, with emphasis on restraining technological advances and testing hardware thoroughly. Other subsystems, the engine in particular, pushed the state-of-the-art considerably. In many ways, not unlike previous programs, such subsystems went into production while still relatively immature. Consistent with previous experience, the more immature subsystems have increased program cost, required extensive modifications, and reduced system effectiveness; the relatively conservative airframe design has caused, on the other hand, very few problems.

Much of the F-15 program success has been attributed to the relatively long time between program go-ahead and first flight.[2] As shown in Figure 15, this period covers about 31 months. A comparison

---

[1] *Aviation Week & Space Technology*, August 13, 1979, p. 16.

[2] *Aviation Week & Space Technology*, October 29, 1973, p. 52.

with Figure 11 shows that this period lasts about 7 months longer than in the F-111 program. Though probably a contributing factor, it seems unlikely the 29 percent longer schedule explains all the relative success of the F-15. The relatively lower sophistication of the airframe and the development philosophy--specifically, intensive testing and design conservativeness--probably explain as much of the relative F-15 airframe success. And, even though the F-15 program did not go into full-rate production until three years after first flight, a comparison between Figures 11 and 15 shows that the F-111 and F-15 production schedules hardly differed at all. Thus, the acquisition policies of the 1970s have affected the F-15 production schedule only minimally. Furthermore, the engine and avionics programs seem to have utilized few of the new acquisition policies and produced problematic subsystems.

The F-15 acquisition cycle has occupied a period of rapid electronics technological advances which have affected F-15 design and capabilities. By the late 1970s a Programmable Signal Processor (PSP) became available; it allows the pilot to use the F-15 radar to distinguish the number and location of hostile aircraft beyond visual range.[1] The PSP increases the F-15 radar capability significantly, at a cost of nearly $400,000 per aircraft.[2] The high cost, however, has limited implementation to only the C and D models. The growing enemy electronic threat, permitted by technology advances, has necessitated an update modification on the F-15 Radar Warning Receiver (RWR). These improvements have cost about $15 million for 640 aircraft.[3] On the other hand, electronic technology advances have allowed central computer cost reductions of $10,000 per unit, while doubling computer memory, and have permitted a radar cost reduction of 10 percent.[4] Thus, the F-15 has taken advantage of technological advances to both improve capabilities and reduce costs.

---

[1] *DMS Market Intelligence Report*, Greenwich, Connecticut, 1979.

[2] Estimated from original ECP information.

[3] *DMS Market Intelligence Report*, Greenwich, Connecticut, 1979.

[4] *Interavia*, December 1978, pp. 1178-1179.

B. STRUCTURING THE F-15 AS A PAS PROGRAM

The F-15 Program and the Theoretical Model

This study considers the effects of acquisition strategy features, within the bounds of the narrowed theoretical model, on F-15 airframe and avionics costs and effectiveness. It does not explore effects on development of the engine, one of the more troublesome F-15 subsystems.[1] The airframe and avionics developments fit the previously described theoretical model reasonably well.

The F-15 program emphasized minimizing design risk and incorporated a modest initial, low-rate production phase with extensive flight tests.[2] It used 20 pre-production aircraft to verify the airframe design, though the early flight program was not unusually intensive.[3] Thus, the F-15 program did have an initial, low-rate production phase, coupled with an early flight testing program, much as prescribed by the theoretical model. No fundamental restrictions preclude variations in these activities to make them more consistent with a PAS program.

Design modifications took place during the early F-15 production years. An ECP process, similar to that described earlier, managed the various design changes. Compared to other programs, relatively few ECPs originated early in the life cycle. Several resulted from deficiencies highlighted by early operating experience. Others came about because of technology advances or threat increases. A relatively

---

[1] This analysis does not include the engine for two reasons. First, a separate program office has managed F100 acquisition and much F100 data, therefore, appear in sources separate from those containing other aircraft data. Second, use of the F100 in the F-16 aircraft would complicate an analysis of F100 applications in the F-15.

[2] Note that the tooling for the pre-production aircraft was intended to be "hard," in that it matched production tooling closely, and did not permit easy, low-cost changes.

[3] Compared to the F-111 program, the F-15 had about one thousand flight hours more at delivery of the twenty-first aircraft. A comparison of the two programs shows that this resulted mainly because the time between first and twenty-first aircraft delivery took four months longer in the F-15 program; flight rates on individual aircraft did not vary significantly between the two programs. Therefore, in terms of individual aircraft, the F-15 did not have an exceptionally intensive early flight program.

comprehensive data system records the history of each ECP.[1] The ECPs originated and generated aircraft modifications continuously over time, rather than all at a specific point in time. Consequently, each ECP affects a different number of aircraft in retrofit and on the production line than do other ECPs. Most F-15 ECPs have had modest consequences, but some, such as the PEP-2000 fuel-capacity modifications, have had significant cost and effectiveness consequences. Thus, the F-15 program has had a modification process similar to that included in the theoretical model; it had both retrofit and production-line components; it resulted in part from operating experience; and it increased aircraft effectiveness, at a cost.

The Air Force has tracked characteristics related to F-15 effectiveness levels. Operational readiness data yield one aggregate measure of aircraft availability and capability to perform its mission. Maintenance and reliability data generate average availability. A good direct metric of aircraft capability, however, does not exist. The F-15C, because of the PEP-2000 and PSP modifications, clearly has a higher capability level than the F-15A, but no good means exists for comparing their capabilities. As modifications enter each aircraft, its capability and availability change; since modifications do not take place simultaneously for all aircraft, the effectiveness level varies from one aircraft to the next. Thus, data systems provide approximate measures of F-15 effectiveness, but not in the rigorous way assumed in the theoretical model. Furthermore, not all F-15s achieved the same final effectiveness level at the end of a specific modification phase, as suggested by the model.

The F-15 program has had a phase that delivered pre-production aircraft and one that delivered production aircraft. Production rate increased fairly gradually for about three years, then increased

[1] ECP effects on production costs, however, typically elude accurate accounting. This requires special attention in the analyses of each ECP.

quickly to a higher level. The production rate has varied significantly from original plans, as has the program schedule. Thus, even though the program has had low- and high-rate production phases, no clear demarcation separates the phases, as suggested by the model. And, unlike in the model, production rates have deviated from original plans.

Finally, inflation has affected the F-15 program significantly. High inflation rates caused program cost increases which, in turn, caused production rate decreases. The theoretical model does not incorporate potential effects of inflation.

Accommodating the F-15 Program to a PAS Approach

The means of accommodating the F-15 program to a PAS approach parallels that utilized for the F-111. Therefore, this sub-section discusses only the differences that the F-15 program introduces.[1]

Details available in the F-15 ECP data used in this analysis make it possible to identify ECPs that might depend more on calendar time than flight time. ECPs which originate because of technological advances would originate in alternative acquisition scenarios at the same calendar time, regardless of flight time. For the remaining ECPs, I assume the flight-time criterion holds, as discussed earlier.

Available F-15 ECP data also make it possible to estimate some military man-hour effects of modifications. Retrofit modifications often require military labor to implement, and the data base permits estimating labor requirements of the ECPs and associated costs, given a military wage rate.

Several F-15 ECPs have obvious effectiveness impacts. No clear distinction exists to define effectiveness-limited aircraft, as occurs in the F-111 program, but the available information permits some qualitative assessments of effectiveness constraints.

---

[1]For other details see the discussion in Section V.

C. F-15 ANALYSIS METHODOLOGY

Simulation Overview

The analysis of alternative F-15 program scenarios uses a computer simulation model similar to that used in the F-111 analysis. It covers costs associated with ECPs originating between the beginning of 1974 and the end of 1978. It also includes the effectiveness impacts of a few ECPs originating later. The model separates ECPs into those depending primarily on (1) flight time and (2) calendar time, and calculates their individual costs. It estimates program effects under scenarios defined by different production- and flight-rate inputs.

Initial and Full-Scale Production

The F-15 simulation encompasses the period from two years after first aircraft production until two years into full-scale production. The analysis starts at this point because the actual program produced so few ECPs before this time. The low ECP generation frequency early in the F-15 program also necessitates the relatively long time period to capture a reasonable number of ECPs in the analysis.

For the same reasons as in the F-111 analysis, the F-15 simulation does not estimate how alternative scenarios might affect production costs. Though different production rates might alter production costs significantly, no technique exists for estimating such effects. Furthermore, the unplanned production-rate variations in the actual program would complicate such an analysis.

Follow-On Development and Initial Operations

The F-15 simulation model does not estimate follow-on development cost effects, for the same reasons as in the F-111 analysis. Under the most attractive and relevant alternative scenarios, follow-on development costs probably differ an insignificant amount from their value in the actual program.

This analysis also does not estimate operating costs during the initial-operations phase. Since the F-111 results indicate that early operating costs may decrease in PAS scenarios, neglecting the effects may simply make the results more conservative. In any case, the effects tend to be negligible over the life cycle.

Production-Line Modifications

Most modifications affect subsequent production aircraft on the production line. The date associated with each ECP, whether driven by calendar or flight time, determines the number of aircraft requiring production-line modification.

Production-line modifications usually have both non-recurring and recurring cost components.[1] The non-recurring cost remains the same, regardless of production quantity, while recurring cost represents a constant incremental cost per production unit. In alternative scenarios where more aircraft modifications take place on the production line, production-line modification costs increase.

Retrofit Modifications

Most modifications affect previously produced aircraft through retrofit. The number of aircraft already produced when each ECP originates, whether driven by calendar or flight time, determines the quantity of aircraft retrofit through that ECP.

Retrofit modifications usually entail non-recurring and recurring costs and require a quantity of military labor. Non-recurring retrofit costs do not vary under different scenarios unless a particular strategy completely eliminates the need for certain retrofit modifications, thereby eliminating their associated fixed costs. Retrofit recurring costs usually have a fixed value, per unit modified; likewise, estimated retrofit labor usually equals a constant amount for each unit retrofit. Typical alternative acquisition strategies usually reduce the quantity of aircraft retrofit, thus reducing retrofit costs and labor.

Data Used in the Analyses

The F-15 simulation analysis uses four basic data elements from the actual program: ECP costs, retrofit labor, production rates, and flight rates.

The F-15 SPO has compiled information on each ECP submitted. I obtained the necessary data on ECPs submitted from 1974 through

---

[1]Non-recurring costs average about one-hundred times recurring costs for both production-line modifications and retrofits.

1979.[1] Of the ECPs covering this time period, I eliminated those requiring expenditures of less than $500,000; the remaining 54 ECPs captured nearly 85 percent of the $270 million spent in ECPs during this period. Several of the ECPs involved no retrofit or only modification to ground equipment. Since these would not benefit from acquisition strategies that reduce the quantities of aircraft retrofit, most were eliminated from the sample. The only exceptions were ECPs that had clear effectiveness impacts.[2] The remaining sample contained 29 ECPs. These ECPs cost about $122 million to implement. Excluding the costs of the remaining ECPs with effectiveness impacts, but no retrofit component or unlikely to depend on acquisition strategy, reduced the relevant costs to $42.3 million.[3] For these ECPs, the data base provided information on retrofit labor, recurring and non-recurring costs and production line recurring and non-recurring costs.[4]

Of the twenty-nine ECPs in the sample, twenty-four appeared flight-time dependent--that is, the date when they originated probably depended mostly on the quantity of operating data available. The remaining five appeared to depend mostly on calendar time because they resulted from exogenous events, such as technological advances. This group included incorporation of the PSP.

---

[1] Personal communications with Colonel John Mantei, F-15 Configuration Control Board, Wright-Patterson Air Force Base, Ohio, September-December 1980.

[2] That is, if a given ECP only occurred in production but significantly improved aircraft effectiveness, it remained in the sample since alternative acquisition scenarios would probably increase the quantity of aircraft produced with that modification.

[3] Several ECPs whose costs were deleted involved large expenditures. One allocated $25 million for the production-line installation of PEP-2000 modifications. Another required $28 million for only production-line installation of the PSP. And, a third simply shifted $16 million from production-accounts to retrofit-accounts to cover retrofit of the Tactical Electronic Warfare Systems (TEWS), which was not ready during several early years of production.

[4] See Appendix E for details of the F-15 ECPs.

Table 17 presents the number of F-15s accepted annually and cumulative flight hours. The acceptance rate provides a reasonable proxy for production rate; the simulation model includes the monthly data as F-15 production rates for each month covered by the analysis. The production rates and cumulative flight hours provide adequate information for estimating monthly flight rates per aircraft. The simulation includes these data as the average monthly flight rates.

Scenario Variables

Monthly production rates and flight rates define alternative acquisition scenarios. In the simulation model, production rates and flight rates, relative to those in the actual program, characterize each alternative scenario.

The simulation model also permits a subset of aircraft to consitute a "lead-the-fleet" group. This analysis uses the same options as the F-111 analysis does--namely, a fixed number or fixed proportion of production F-15s may be designated as lead-the-fleet aircraft.

Table 17

PRODUCTION AND FLIGHT DATA[a]

End of Fiscal Year	Cumulative Aircraft Delivered	Cumulative Flight Hours
1973	7	205
1974	16	1,877
1975	36	4,860
1976	90	13,776
197T[b]	127	18,796
1977	246	55,453
1978	346	118,214
1979	459	207,817

[a]Source: *USAF Statistical Report*, various years.

[b]Includes three-month transition (T) period to new USG fiscal year.

Four basic parameters then completely specify each alternative acquisition case in the simulation. These parameters include (1) the relative production rate, (2) the relative average flight rate, (3) the proportion or number of aircraft in the lead-the-fleet program, and (4) the flight rate of lead-the-fleet aircraft.

Simulation Model

Figure 16 presents a schematic of the F-15 simulation model. In general, its structure and operation do not differ significantly from the F-111 model, shown in Figure 12.

The simulation model uses input conditions that specify flight and production rates relative to the actual program. It calculates cumulative flight hours and aircraft, at the end of each month, for a seven year period starting in January 1974. It then compares the cumulative flight hours with those required to generate each of the twenty-four flight-time dependent ECPs. It then calculates the ECP-generation date for these ECPs as the month when cumulative flight time first exceeds the quantity associated with each ECP.

For the five remaining ECPs, the simulation uses internal data to determine the generation date. The ECPs have a calendar-time dependence; therefore, in all alternative scenarios, they originate in the same month as in the actual program.

The simulation then uses the input production rates to determine the number of aircraft produced by each ECP-generation date. The simulation model next determines retrofit costs for each ECP, using the number of aircraft produced and the retrofit data. It calculates retrofit manhours, retrofit recurring cost, and retrofit non-recurring cost for each ECP and the complete set. It then calculates production-line modification costs for each ECP.

The output consists of three parts for each case. First, it presents the cumulative aircraft, lead-the-fleet aircraft, and cumulative flight hours for each month in the analysis. Second, it presents information for the flight-time dependent ECPs. It shows the ECP number, retrofit labor, retrofit recurring and non-recurring costs, production-line recurring and non-recurring costs, and the numbers of

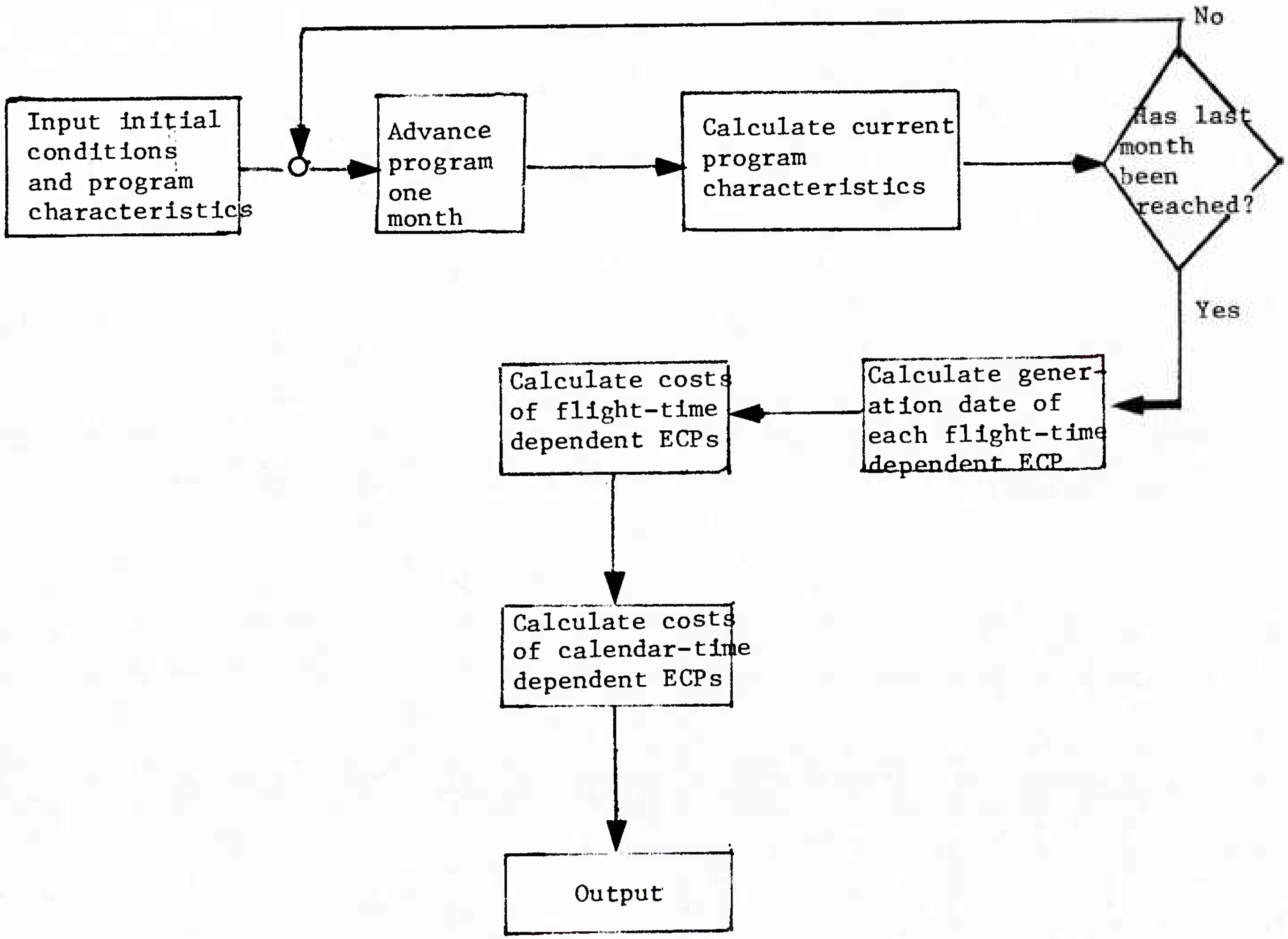


Fig. 16--F-15 simulation model schematic

aircraft retrofit and modified on the production line. Third, the output presents the same information for the calendar-time dependent ECPs.

D. SIMULATION ANALYSES AND RESULTS

Objectives

The simulation model indicates how variations in production rates, flight rates, and lead-the-fleet program characteristics could affect F-15 program outcomes. It permits exploring the effects of each parameter individually or in combination with variations in other parameters. The simulation model estimates parameter effects on modification costs, retrofit labor, and basic measures of effectiveness.

This section presents the results, in the same sequence as in the F-111 discussion. First, it describes the actual F-15 program, the base case, and examines the potential for program improvements. Next, it discusses production-rate effects. Third, it presents flight-rate effects. Fourth, this section examines lead-the-fleet program effects. Finally, it discusses the consequences of a mixed strategy, representative of a PAS approach.

Base Case--The Actual F-15 Program

This analysis uses the actual F-15 program as the reference, or base, case. When the analysis begins, at the start of 1974, the fleet consists of the first eleven pre-production aircraft. The production rate averages about one aircraft per month during 1974, increases to about three per month in 1975, and increases to nearly nine per month the following year. By 1977 the rate reaches about ten aircraft per month, essentially the average full-scale production rate. For the first two-and-a-half years, the monthly flight rate stays around eleven flight hours per aircraft. Afterwards, it gradually increases to between eighteen and twenty hours per month. The base case includes no specific lead-the-fleet flight program.[1]

---

[1]Interestingly, however, a lead-the-fleet program of ten engines began in early 1978 after significant engine problems developed. See *Aviation Week & Space Technology*, February 6, 1978, p. 72.

In the base case, the 22 ECPs, for which the simulation estimates the cost effects, require total modification expenditures of $42.3 million.[1] The costs of the remaining seven ECPs in the sample would contribute an additional $80 million, but their costs have been deleted for reasons discussed earlier. The 22 ECPs require retrofit expenditures of $20.1 million and production-line expenditures of $22.2 million. In addition, retrofit requires 415,000 man-hours of military labor. Using one estimate of the fully-burdened military labor wage, this could add an additional $6.2 million to estimated retrofit costs.[2] The base case generates the last of these 22 ECPs by December 1978.

The remaining seven ECPs primarily have effectiveness implications. Of them, the two major ones involve installation of the PEP-2000 fuel capacity modifications and incorporation of the Programmable Signal Processor. The PEP-2000 modification probably depends mostly on flight time, while the PSP installation depends principally on calendar time. The following table, Table 18, illustrates the effectiveness impact of these modifications.

Table 18

IMPACTS OF EFFECTIVENESS ECPs

ECP Number	Description	Effectiveness Impact
450	Installs PEP-2000 production-line changes to increase aircraft fuel capacity	415 aircraft produced with smaller fuel capacity; 314 aircraft eventually have larger fuel capacity
937	Installs PSP on production-line aircraft to increase radar capability	497 aircraft produced without PSP

[1]Note that these and following estimates derive from the simulation model recreation of the F-15 program and may not equal the actual program values precisely. However, the simulation model duplicates program values to within a few percent.

[2]Personal communication, Major Roland Witherell, Wright-Patterson AFB, Ohio, (December 1977). He provided an estimate of about $15 per hour in 1975 dollars.

Nearly 60 percent of all F-15s are produced before the PEP-2000 modifications become available. And, the Air Force receives nearly 500 F-15s, almost 70 percent of the total buy, before availability of the PSP.

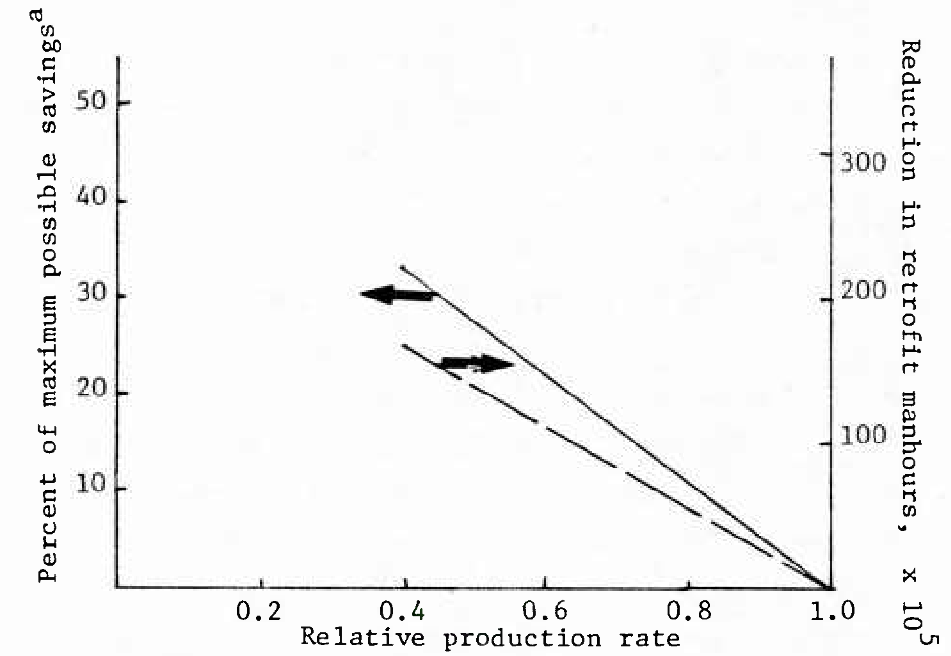
Under the acquisition strategy variations explored here, modifications shift from retrofit to the production line. In the extreme case, all changes would occur on the production line and no retrofit would take place. In this situation, retrofit manhours could equal zero and the program would avoid all retrofit costs, including the non-recurring component. Only production-line modification costs would remain, for a total of $22.9 million. The difference between this extreme case and the base case defines the maximum potential savings. This amount equals $19.4 million, and subsequent discussions present savings relative to this maximum potential amount. For perspective, this potential modification cost reduction equals about the cost of two F-15 aircraft and represents only about 0.2 percent of total program costs. This small effect affirms the minimal role that modifications, other than those for the engine, have played in the F-15 program.

Production-Rate Effects

As it does in the F-111 program, decreasing the production rate reduces F-15 modification costs. It also reduces the quantity of retrofit labor required.

Figure 17a shows the effect of production rate on modification costs and retrofit labor.[1] Savings increase almost linearly as relative production rate falls. For each 10 percent decrease in relative production rate, savings increase about 5.6 percent of the maximum amount possible. At one-half the actual production rate, savings equal about 27 percent of the maximum amount possible, or about $5.2 million. Retrofit labor also varies almost linearly with production rate. For each 10 percent decrease in relative production rate, labor decreases by about 28,000 manhours. At one-half the actual production rate the program requires about 132,000 less retrofit manhours than the actual program does.

[1]Note that none of these results include estimates of military labor costs.



[a]Maximum possible savings = \$19.4 million.

Fig. 17a—F-15 production rate modification effects, holding all other program characteristics at actual program values.

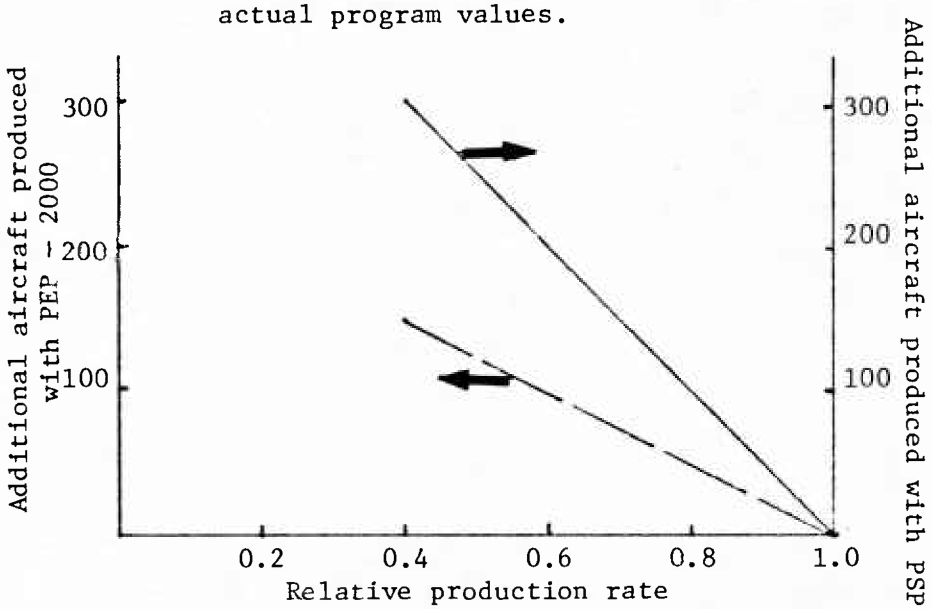


Fig. 17b—F-15 production rate effectiveness impact, holding all other program characteristics at actual program values.

Figure 17b shows some effectiveness impacts of production rate. The figure shows how relative production rate affects the number of aircraft produced without two of the major modifications that improve F-15 effectiveness. The lower curve shows how relative production rate affects the number of F-15s produced without the PEP-2000 modification. This modification significantly increases F-15 effectiveness by adding fuel capacity. As relative production rate decreases, fewer aircraft are produced before the PEP-2000 modification originates. The bottom curve shows that the number of aircraft produced with PEP-2000 increases linearly as production rate decreases. For each 10 percent decrease in production rate, the number of aircraft produced with PEP-2000 increases by 27. The upper curve shows a similar phenomenon for installation of PSP. For each 10 percent drop in relative production rate, the number of aircraft produced with the PSP increases by 51. These results indicate nothing about the timeliness of these two modifications. They do, however, show that lower production rates could significantly increase the number of aircraft that incorporate effectiveness-enhancing modifications during production.

Production rate decreases appear to have considerable potential for improving the outcomes associated with F-15 modifications in this sample. Production rate has a linear effect on modification cost savings, retrofit manhours, and one measure of fleet effectiveness. Production rate affects outcomes associated with both flight-time and calendar-time dependent ECPs. Most production rate effects become significant when production rate falls to about six-tenths of the actual program values.

Flight-Rate Effects

As explained in the F-111 discussion, modification costs of flight-time dependent ECPs decrease when flight rates increase. Costs of calendar-time dependent ECPs, however, do not vary when only program flight rates change. This occurs because the ECP originates on the same date in alternative scenarios and, when production rates do not vary, the same number of aircraft require retrofit.

Figure 18a shows the effect of relative flight rates on modification cost savings and retrofit labor. Cost savings increase rapidly for flight rates up to about two times the actual rates. Thereafter, savings increase with flight rate but at a diminishing rate. At double the actual program flight rate, savings equal about 23 percent of the maximum possible amount. The reduction in retrofit manhours follows a similar pattern. At double the actual flight rate, retrofit labor declines by 139,000 manhours.

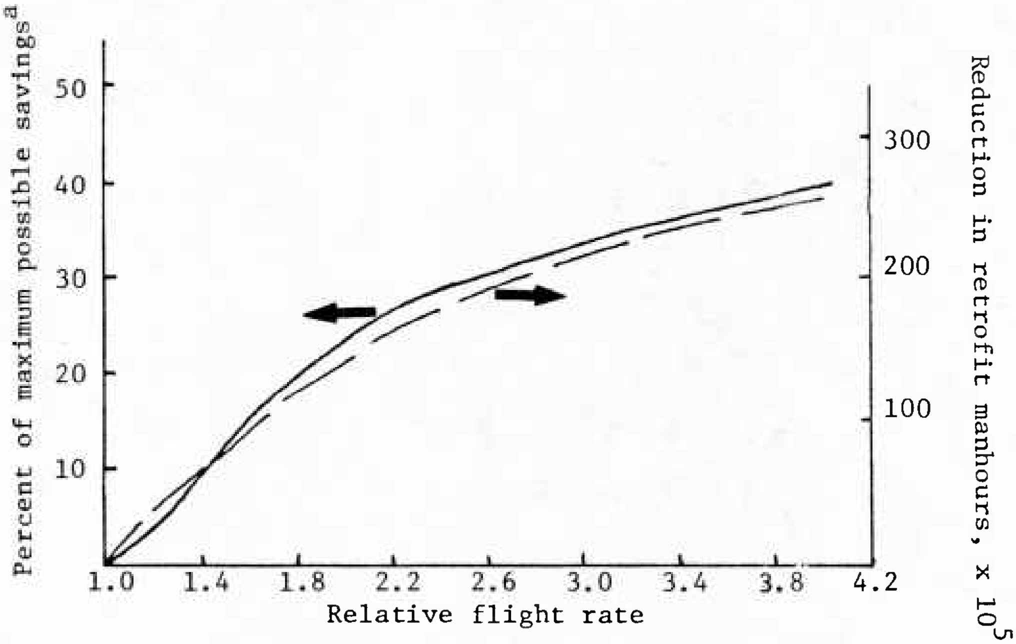
Figure 18b presents one impact of flight rate on effectiveness. The plot shows the number of additional aircraft produced with the PEP-2000 modification. It follows a pattern similar to the other flight rate effects. At double the actual flight rate, 117 additional aircraft would have the PEP-2000 changes installed on the production line. This plot does not show effects on PSP incorporation because the PSP modification appears more calendar-time dependent; as discussed above, such ECPs would not have different retrofit and production-line effectivities when only flight rate varies.

Increases in flight rates have some potential for improving outcomes associated with F-15 modification included in this study. Flight rate appears to have marginally decreasing effects as flight rate increases. The most benefits appear to occur up to flight rates about twice the actual program values. Doubling the flight rate produces about the same effects as decreasing the production rate 50 percent. Flight rates, however, do not have effects on those ECPs dependent on calendar time.

Lead-the-Fleet Effects

This analysis considers two potential lead-the-fleet approaches for the F-15 program. The F-111 discussion explains their characteristics and potential effects.

Table 19 presents the effects of several illustrative lead-the-fleet approaches. The first two utilize 10 aircraft in the lead-the-fleet program. When this group has a flight rate double the actual value, modification cost savings equal only 8 percent of the maximum possible amount; at four times the actual flight rate savings increase



[a]Maximum possible savings = $19.4 million

Fig. 18a—F-15 flight rate modification effects, holding all other program characteristics at actual program values.

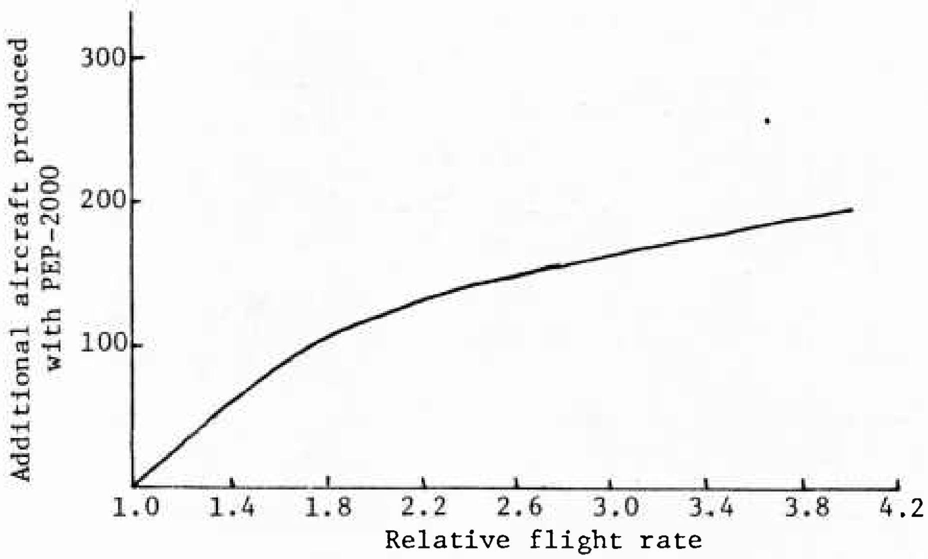


Fig. 18b—F-15 flight rate effectiveness impacts, holding all other program characteristics at actual program values.

Table 19

F-15 LEAD-THE-FLEET EFFECTS

Lead-the-Fleet-Program					
Initial Lead-the-Fleet Aircraft	Proportion of Production Lead-the-Fleet Aircraft	Lead-the-Fleet Flight Rate[a]	Modification Cost Saving, % of Maximum Possible[b]	Military Labor Reduction, Manhours[c]	Additional Aircraft with PEP-2000 Modifications
10	--	2	8	26,000	12
10	--	4	24	84,000	29
0	0.2	2	3	32,000	29
	0.2	4	13	80,000	92
0	0.4	2	8	57,000	62
	0.4	4	21	133,000	123

[a]Relative to flight rate in actual program.

[b]Maximum possible savings = $19.4 million.

[c]Actual program required 415,000 retrofit manhours.

to 24 percent. Retrofit labor decreases 26,000 and 84,000 manhours in the two programs, respectively. The next four cases show the effects of assigning a constant proportion of aircraft to the lead-the-fleet program. Savings vary from 3 percent--when two-tenths of all aircraft fly at twice the actual flight rate--to 21 percent--when four-tenths of all aircraft fly at four times the actual flight rate. Retrofit labor savings increase less, from 32,000 to 133,000 manhours.

Table 19 also shows how lead-the-fleet strategies impact effectiveness, through their effect on the number of F-15s incorporating PEP-2000 changes on the production line. When 10 aircraft fly at twice the actual program rate, the number of aircraft produced with PEP-2000 changes exceeds the number in the actual program by only 12. At the other extreme, this number increases to 123 when four-tenths of all aircraft fly at four times the actual program rate. These results do not show any effect on installation of the PSP because, again, no effect occurs when only flight rates vary.

The lead-the-fleet approaches appear to have only marginal effects on program outcomes. Only the more extreme lead-the-fleet approaches produce effects comparable to those of decreasing the production rate by 50 percent. Further, lead-the-fleet approaches do not affect outcomes associated with calendar time dependent ECPs.

Representative PAS

By combining production rate, flight rate and lead-the-fleet approaches, we can explore programs typical of the PAS approach. Such combinations may avoid some of the probable implementation difficulties of large variations in a single parameter, such as flight rate.

I have defined a representative, but not optimized, F-15 PAS program as follows:

- Production rates in 1974 and 1975 equal their values in the actual program--about one and three aircraft per month, respectively.

- Production rates in 1976 equal three-tenths their actual program values--about three aircraft per month in the PAS case.
- Production rates in 1977 equal half their actual program values--about five aircraft per month in the PAS case.
- Production rates equal their actual program values thereafter.
- A lead-the-fleet group consists of ten initial aircraft and half the aircraft produced through 1976--a total of 47 F-15s.

The simulation analysis then provides the results for two PAS programs using these parameters and the flight rates shown in Table 20 below.

These results show the advantages of combining different techniques. Specifically, the PAS approach extends the low-rate production phase, and utilizes a group of aircraft flown in an intensive flight program. With most aircraft flown at the rate in the actual program and the lead-the-fleet group flown twice as much, program outcomes compare favorably to even the most extreme variations considered earlier. A doubling of both these flight rates increases cost savings to almost half the maximum possible amount. It reduces retrofit labor by 284,000 man-hours, or about $4.3 million. And, it increases the number

Table 20

REPRESENTATIVE PAS PROGRAM RESULTS

Relative Flight Rate		Savings, % of Maximum Possible[b]	Retrofit Labor Reduction, Man-Hours	Additional Aircraft Produced with	
Basic[a]	Lead-the-Fleet			PEP-2000	PSP
1	2	36	180,000	90	132
2	4	49	284,000	232	132

[a]Basic Relative Flight Rate applies to all aircraft not in the lead-the-fleet group.

[b]Maximum possible savings = $19.4 million.

of aircraft with PEP-2000 changes by 232. The number of aircraft produced with the PSP remains 132 more than in the actual program.

This case illustrates how a reasonable combination of program variations may provide both cost and effectiveness advantages. In prior cases, in which only a single parameter varies, obvious factors tend to counteract some of the calculated benefits. For example, though high flight rates alone can reduce modification costs, they may present serious support problems. Here, however, combinations of feasible variations in several parameters appear to provide major benefits in all three output measures--costs, labor, and effectiveness--without imposing obvious, major costs in other areas.

E. CASE STUDY SUMMARY

Characteristics of Actual Program

The F-15 program required modest technological advances and made moderately good use of the acquisition strategy to resolve design uncertainties.[1] The strategy emphasized design conservatism and sequential decisionmaking. Planners appeared to benefit from previous lessons in terms of timely testing and use of test data.

The program has produced a relatively successful design. Design deficiencies have been relatively sparse, involving only moderate expenditures. Technical performance has met most expectations, but effectiveness has suffered from low reliability and parts shortages.

Expectations Based on Research Findings

The F-15 program reflected the insights provided by past research more than either of the other two programs studied here. But, even though the program emphasized design conservatism, the design certainly did represent an advance over available designs. The acquisition program also emphasized conservatism in terms of timing and commitments. As noted earlier, however, the F-15 program did not appear *significantly* more conservative than the F-111 program. In combination

---

[1] Note again that this analysis has excluded the F-15 engine which has had a quite different history.

though, the relative design and acquisition strategy conservativeness should have led, in light of previous research, to a moderately successful program.

The theoretical model would have probably provided mixed indications of the advantages of PAS in the F-15 program. The relatively small retrofit costs would not have strongly encouraged a PAS approach. The early emphasis on production tooling, during the pre-production phase, however, contradicted the principles behind PAS. Though the model did not include this factor explicitly, emphasizing production tooling early would have necessarily increased the costs of making subsequent tooling changes. Thus, the model would have led to expectations of modest cost reductions from applying PAS to the F-15 program.

Overall, we would have expected the F-15 program to benefit only moderately from PAS. This expectation resulted from both the minimal system design uncertainty and the relatively conservative acquisition program actually employed.

PAS Effects

This analysis has paralleled that employed in the F-111 case study to estimate PAS effects in the F-15 program. This section defined a representative F-15 PAS scenario as follows:

- Ten initial and half the F-15s produced through 1976 enter the lead-the-fleet group.
- Lead-the-fleet flight rate equals twice the average in the actual F-15 program.
- All other F-15s fly at the average rate in the actual program values in 1976 and increased their actual program values after one more year.
- Production rates in 1974 and 1975 equal their values in the actual program.
- Production rates equal three-tenths their actual program values in 1976 and increase to their actual program values after one more year.

This PAS scenario led to the following results:

- o Costs decreased about $7 million.
- o Air Force retrofit labor decreased by 180,000 man-hours.
- o Low-rate production lasted about an additional two years .
- o Overall effectiveness increased modestly.

The cost reductions from decreased retrofit appeared relatively small. Reduced retrofit would have decreased military labor requirements by about 40,000 man-hours per year for five years, saving a total of about $3 million more. The extended low-rate production phase would have reduced the F-15 inventory at the end of 1977 from 246 aircraft to about half that amount. Increased effectiveness would have resulted from incorporation of additional fuel capacity and newer electronics technology on a larger number of aircraft.

PAS could have increased the number of F-15s with higher fuel capacity and advanced technologies. PAS could offer these advantages in any program where related technological and design advances occurred during the course of the program. These improvements would lead to higher effectiveness, but only through a tradeoff which would decrease the number of systems available early in the program. The F-15 PAS scenario demonstrated this tradeoff quite clearly. The F-15 case also showed potential PAS cost savings, but of a small magnitude.

VIII. FEASIBILITY OF IMPLEMENTING PAS

A. FEASIBILITY OF CHANGING THE ACQUISITION STRATEGY DESIGN TO PAS

This research has explored acquisition strategy changes during the early production phase that might improve Air Force program outcomes. It recognizes the important fact that early acquisition activities and decisions may not have their full impacts until many years later. The analysis proposes an acquisition strategy, called PAS, which establishes specific steps to improve program outcomes in terms of life cycle cost and effectiveness. The scope of the research, however, limits the analysis to consideration of activities during the transition from development to production. The acquisition strategy, developed within these bounds, postulates (1) extending the initial low-rate production phase, (2) increasing early flight and test intensity, (3) using lead-the-fleet programs to accelerate the accumulation of operating experience, and (4) using early flight and test information to make timely design changes.

Each of these postulated strategy changes raises feasibility issues. The fact that such variations often arise within and across programs demonstrates that these program characteristics do have considerable flexibility. We need to evaluate whether the changes proposed in this analysis seem feasible compared with variations that occur in actual programs.

Extending the initial, low-rate production phase does not raise any fundamental feasibility issues. The mechanics of setting up a production capability necessitate an incremental build-up in production rate anyway. The question is whether this build-up could take place, essentially, in two stages. There does not appear to be any basic factor that rules out a phased production capacity build-up. The main problem would be the initial underutilization of relatively fixed production inputs, such as production tooling or physical floor space. Underutilization might raise the average cost of initial production units. On the other hand, variable inputs, such as labor, could probably increase at a more gradual rate,

commensurate with production requirements. A less rapid increase in demand for variable inputs might lead to higher efficiencies than conventional programs and, therefore, relative cost reductions. Furthermore, if an extended low-rate production phase and parallel system operating experience result in increased confidence in system design, the subsequent production rate may attain higher levels than otherwise. One study has suggested that this could reduce overall production costs.[1] Because of the magnitude and importance of production costs, this whole issue deserves considerably more attention.

Increasing early flight intensity may raise important feasibility issues. The number of hours available per day and aircraft turnaround time provide the ultimate constraints on flight time. The flight rates early in the F-15 program average about one-third hour per working day, per aircraft. Later, they increase to about one hour per day. Turnaround times probably limit the achievable flight rates to an extent. The turnaround time depends on maintenance requirements and the availability of maintenance personnel and spare parts. Thus, achieving more flight hours on individual aircraft would depend on increased personnel and spare part availability. However, the strategies discussed here combine higher flight rates per aircraft with lower production rates; as a result, the profiles of aggregate flight time do not differ greatly between the alternative strategies and the actual program. Thus, the individual aircraft may require more maintenance and operating support, but the total requirements may not differ. There is no question, though, that individual aircraft flight rates beyond a certain level would be unattainable. However, the promising PAS scenarios, discussed earlier, show that modest increases in early flight rates--to perhaps 0.7 hours per day in the F-15 program--would provide most of the potential benefits.[2]

The feasibility of increasing test intensity depends on the nature of the items being tested. Fatigue testing of structural

---

[1] Dreyfuss, David, and Joseph Large, *Estimated Costs of Extended Low-Rate Airframe Production*, The Rand Corporation, R-2243-AF, March 1978.

[2] Note that the contractor projected F-15 sortie rates at 3.5 sorties/day, at 2 hours per sortie. See *Aviation Week & Space Technology*, April 1, 1974, pp. 50-53.

components has relatively high costs because of requirements for large equipment, and requires much time because fatigue lifetimes may be several thousand hours. Tests of electronic components may, on the other hand, require relatively little time if the tests use multiple items and the results extrapolate well to the typical component. However, such tests face validity problems if operational use differs significantly from test conditions. Selecting, and even defining, the proper test intensity presents serious problems. In many ways, however, the F-15 program provides evidence that test intensity has increased.

Lead-the-fleet programs raise the same feasibility issues as increased flight rates, but on a smaller scale. Supporting a few aircraft at high flight rates should place less demands on the support system than would supporting all aircraft at higher rates. However, producing as much information in both alternatives would necessitate larger lead-the-fleet flight rates; the necessary rates might exceed those supportable under ordinary circumstances. For example, the lead-the-fleet aircraft in the more extreme F-15 PAS case fly at four times the rate in the actual program. Even though they number only 47 out of an eventual 729 aircraft, generating an average of 4 flight hours per day might require doubling the daily shifts supporting the lead-the-fleet aircraft. Maintaining the individual identity of lead-the-fleet aircraft components might also present problems. Using lead-the-fleet data would require separately tracking the experiences of these components and separately estimating their failure rates, repair requirements, etc. This would definitely place special demands on the support system. The fact that lead-the-fleet programs do exist, however, demonstrates that these problems are manageable.[1]

Finally, using early flight and test information to make timely design changes should present no serious feasibility problems. In conventional programs, early flights and tests provide initial information about system deficiencies. Often, however, data communication does not occur adequately--one example is the failure of the F-111 contractor to inform the Air Force adequately of early flight tests

---

[1]Airlines frequently utilize lead-the-fleet programs to provide early warnings of potential problems.

stall problems. In other cases, the validity of early information may be questioned and additional tests may be required--in the C-5A program, for example, early evidence suggested wing design deficiencies but this led to more testing rather than early redesign. The communication problem appears less severe in recent programs and should improve as operational testing assumes a more important role. The question of test validity will remain, of course. However, more intensive testing should improve the quality of early information, and reduced production schedule pressures should reduce impediments to making early design changes.

B. POLICY IMPLICATIONS OF IMPLEMENTING PAS

Necessity for Life Cycle Perspective

The first section in this dissertation establishes the importance of considering life cycle consequences early in the acquisition process. The importance of developing a life cycle perspective comes about because of the potentially long delay between early decisions and their impacts, and the very large magnitude of the eventual impacts. In the Air Force environment, however, separate agencies share in different costs and benefits at different times. Therefore, the perspective of each agency includes only certain costs and benefits. Only at the level of the Secretary of the Air Force do all costs and benefits interact to provide an overview of life cycle considerations.

The theoretical analysis and case studies show the potential importance of minimizing concurrency, phasing the production process, conducting early flights and tests, and making timely use of flight and test information. The parameters that characterize each of these activities constitute crucial acquisition decision variables. From a life cycle perspective, each of these variables has consequences that extend beyond their short-term impacts. For example, initial production rates determine short-run system availability. In the long-run, however, the production commitments implied by the early production rate may determine the ease and fate of system

redesign; these impacts may exceed those associated with the quantity of early systems available. Thus, decision variables such as initial production rate and quantity must be chosen with attention to their long-term, as well as immediate, consequences.

Clearly, the Air Force has responsibility for establishing a life cycle context. The contractor simply responds to purchaser requirements by trying to satisfy a corporate goal, within the constraints established by the contract. The contractor has no internal need for considering the life cycle implications of the system it develops. The need can only come by way of incentives instituted by the Air Force.

The Current Policy Context[1]

Current acquisition management and decisionmaking follows several levels of directives, policies, and guidelines that number in the hundreds. Fundamental policy direction originates in OMB Circular A-109; DoD then establishes directives to provide consistent policies for the services, which, in turn, promulgate much more detailed policies applying to the specifics of the acquisition process.

The major DoD Directives delineating acquisition policy consist of the following:[2]

- o DoDD 5000.1--establishes criteria for defining "major" systems; establishes acquisition milestones 0-III; and, establishes guidelines for assigning a program manager, creating the position, and defining the program manager's authority and responsibility.
- o DoDD 5000.2--establishes the DSARC review process and the DCP supporting document.

---

[1]Much of the discussion in this section derives from a good review of acquisition policy presented in: Magee, Terry, *Differences in Aircraft Acquisition Management Practices between the Air Force and the Navy*, Masters Thesis, Naval Postgraduate School, Monterey, California, June 1977.

[2]See Section II for a fuller discussion of these policies.

- o DoDD 5000.3--establishes DoD test and evaluation responsibilities and the requirement for independent test and evaluation.
- o DoD 5000.4--establishes the Cost Analysis Improvement Group and the requirement for independent cost estimating.

The Air Force uses Air Force Regulation 800-2 to implement these policies. Table 21 summarizes the policies established by AFR 800-2.

AFR 800-2 stipulates that the Program Manager (PM) has extensive authority and responsibility in an acquisition program. The major decisions to continue the program occur at higher authority levels, but the PM has responsibility for the day-to-day management decisions that define the acquisition strategy. New communication channels, that partially circumvent the standard chain of command, increase the speed of information flow and should prevent some of the communication problems experienced in programs like the C-5A.[1] To increase program stability, the Air Force has instituted a four-year duty tour for PMs during the first two-thirds of the acquisition cycle and a three-year duty tour during the last third of the cycle.[2] And, early acquisition program success often affects the status and advancement of a PM.

The System Program Office (SPO) has a structure that utilizes a permanently assigned staff separated into functional divisions. Figure 19 presents, as an example, the organizational chart for the F-15 SPO. The directorates, indicated by the lowest set of boxes, cover the major activities during the acquisition cycle. The F-15 program includes a special Joint Engine Project Officer because of engine commonality with the F-16. The Integrated Logistics Support (ILS) Directorate deserves special attention here because it addresses issues related to eventual maintenance and support requirements. The Air Force has attempted to increase the role of ILS during acquisition by utilizing personnel drawn from the Air Force Logistics Command

---

[1]Magee, p. 42.

[2]Magee, p. 54.

Table 21

AFR 800-2 POLICIES

Item	Policies
Headquarters (HQ) USAF	(1) HQ issues the Program Management Directive (PMD); (2) HQ defines the program and provides the Program Manager (PM) charter; (3) HQ designates the Implementing Command (IC); (4) HQ establishes review and approval requirements; and (5) HQ monitors program progress.
Implementing Command	(1) The IC will be designated by HQ USAF to manage an acquisition program; (2) the IC has responsibility for tasks defined by the PMD; and (3) the IC appoints a PM.
Program Manager	(1) A single person will act as PM with delegated authority and responsibility; (2) PM will have minimum interference from all staff officials; (3) PM will make all decisions, except OT&E decisions, under the program as approved by a higher line authority at selected milestones;[a] (4) PM will assess and document how proposed changes may alter program progress and objectives; (5) PM will prepare and issue a Program Management Plan (PMP); (6) PM will ensure adequate communications and coordination; and (7) PM will continuously assess program progress.
Test	(1) Tests during the Demonstration and Validation phase will be conducted to validate one or more designs and provide a basis for proceeding into Full-Scale Engineering Development (FSED); (2) tests during FSED will be conducted to lead to a preproduction system, demonstrate system effectiveness, and provide a basis for entering production; (3) Air Force Test and Evaluation Center (AFTEC) will independently estimate system utility, effectiveness, and suitability.
Communications	(1) PM must promptly report problems to proper line authority; and (2) a direct channel of communication, BLUE LINE, applies in programs specified by HQ USAF.

[a]OT&E is Operational Test and Evaluation.

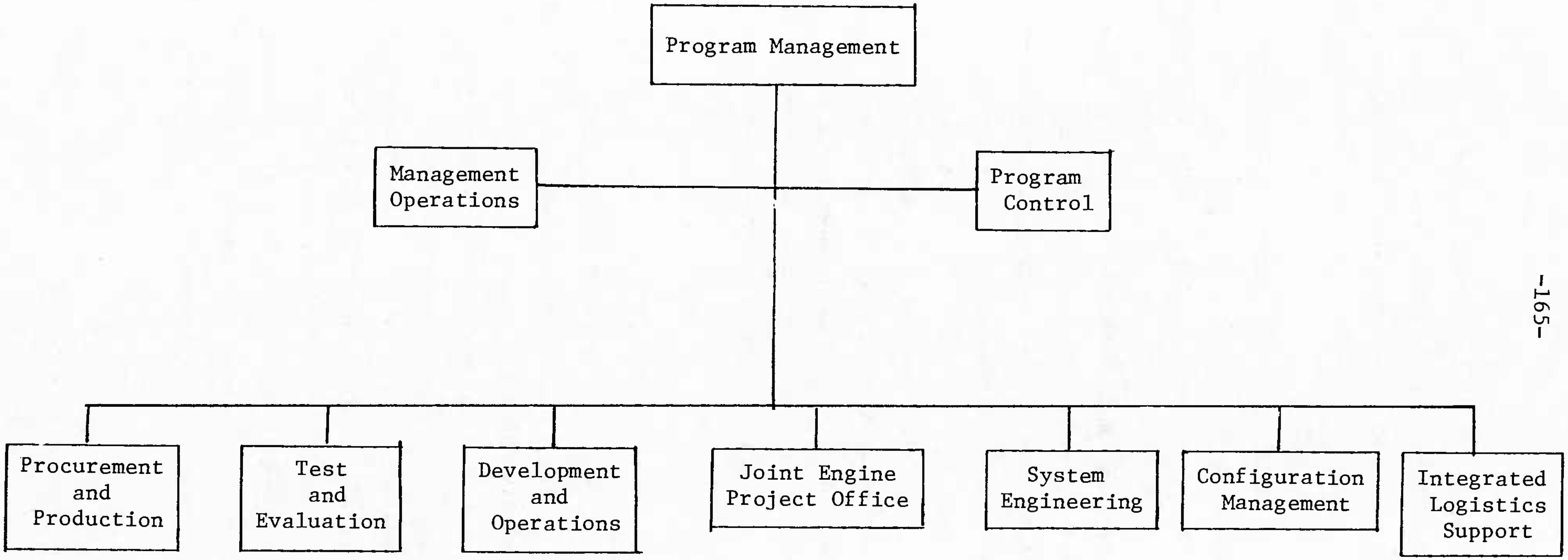


Fig. 19--F-15 SPO organization chart[a]

[a]From Magee.

(AFLC). These people have considerable logistics expertise and are not in the acquisition command chain. However, the PM often gets so involved in the more immediate demands of the acquisition program that he, at times, seems to neglect his responsibility for developing the ILS.[1]

Contractors usually have few incentives for controlling the support requirements of the systems they produce. Contractors tend to emphasize system performance, to the possible detriment of system availability, because the Air Force places a high premium on performance. And, system availability often requires several years to demonstrate, by which time production may be nearly complete. The F-15 program offers some promise because the contract specifies maintenance and reliability guarantees; the enforceability of these guarantees, however, is uncertain.

Contractors generally favor high production rates. Since contractor reimbursement usually occurs through progress payments related to program expenditures, higher cash flows occur when high production rates take place. And, contractors have more leverage in dealing with subcontractors if they have obtained Air Force commitments for large buys.

Future Directions

Policy guidelines, such as A-109 and AFR 800-2, recommend that the acquisition strategy accommodate the exigencies of the particular program. Usually, however, the PM has little information on which to base the selection of an acquisition strategy, or even what program variables might affect program outcomes. This research provides some information about what acquisition program variables can and should be varied, and their probable effects on program outcomes.

This research highlights the importance of initial production rate and quantity, and the utility of initial operating experience. Too often, production rate acts as a variable to control annual costs through Congressional decisionmaking. Though some programs

---

[1] Magee, p. 66.

incorporate low initial production rates and fly-before-buy concepts, using this approach as a way to demonstrate design validity requires more emphasis. Better demonstrations of system effectiveness could reduce Congressional uncertainties, and lead to more program support and stability. The whole issue of production rate effects on production costs deserves more attention; in particular, ways to minimize production costs when production varies from a low-rate to a high-rate phase warrant further investigation. The request to the contractors, in the A-9/A-10 competition, for cost estimates under different production-rate scenarios offers one positive sign that this issue has received some attention.[1]

Lead-the-fleet approaches also deserve more attention. Program planners often institute such approaches when system deficiencies begin to surface--the F100 engine and the TF41 engine in the A-7D are two examples; however, lead-the-fleet deserves attention as an early warning tactic as well.

Many mechanisms exist for providing information on system effectiveness, but they frequently work inadequately to provide early warnings about system problems. The Systems Effectiveness Data System (SEDS) provides reliability and maintainability (R&M) data acquisition, storage, retrieval, and analysis during DT&E.[2] Though SEDS produces several data summaries, they lack adequate detail, cost information, and time trends to provide sufficient information for extensive analyses or projections. One study, using SEDS data from the F-15 program, found about 30 percent of the data incomplete and inconsistencies between raw data and data summaries.[3] Another data system, designed to identify high logistic support cost items during the operating phase, also has demonstrated inadequacies. One

---

[1] Dreyfuss and Large, 1978.

[2] See AFLC Pamphlet 400-11.

[3] Howard, Christopher, *Evaluation of F-15 Operations and Maintenance Costs Based on Analysis of Category II Test Program Maintenance Data*, Air Force Institute of Technology, WPAFB, Ohio, August 1975, p. 92.

study found this system, the Increase Reliability of Operational Systems (IROS), gathers only about 53 percent of base-level maintenance costs and 7 percent of depot-level costs for the A-7D.[1] Clearly, the Air Force process for gathering and interpreting R&M characteristics, that crucially determine system effectiveness, needs substantial improvements.

Finally, the continuity of program management plays an important role in the design of program acquisition strategy. As noted earlier, the Air Force sets the usual PM tenure at four years. Acquisition programs, on the other hand, last two or three times as long; system life cycle may extend over two decades or more. Therefore, a program typically has several officers assigned as PM during the acquisition phase, and all the PMs have moved on when the system completes its service lifetime. Though improvements have been made, the continuity of military program management remains a problem. One study has noted that an experienced civil servant often serves as deputy program manager over a longer time period, and this introduces an element of continuity.[2] Another study stresses the importance of acquisition management and technical experience in improving acquisition outcomes, and recommends creation of an acquisition management corps--this corps, with suitable promotional opportunities, would provide a stable group of experienced managers who would staff each new acquisition program.[3] Whatever the approach, it appears a definite need exists for experienced personnel who can structure and manage each acquisition program, taking advantage of lessons from previous experiences.

In summary, most of the mechanisms exist for implementing the acquisition policy changes explored in this study. Recent acquisition policies, in fact, prescribe strategies largely consistent

---

[1] Fiorello, Marco, and Patricia Konoske-Dey, *An Appraisal of Logistics Support Costs Used in the Air Force IROS Program*, The Rand Corporation, R-1569-PR, February 1975.

[2] Dews, Edmund, G. Smith, A. Barbour, E. Harris, and M. Hesse, *Acquisition Policy Effectiveness: Department of Defense Experience in the 1970s*, The Rand Corporation, R-2516-DRE, October 1979, p. 15.

[3] Magee, p. 97.

with those suggested here. Their fuller implementation appears limited by (1) incomplete understanding of acquisition strategy effects on program outcomes, (2) underestimation of the costs of system deficiencies, and (3) ineffectual use of existing mechanisms for tracking and improving program outcomes.

IX. SUMMARY OF RESEARCH RESULTS AND GENERAL LESSONS

A. SUMMARY OF RESEARCH RESULTS

This research has addressed ways to design the early production phase in Air Force programs to reduce the costs of design changes and increase system effectiveness. It has focused on one specific approach, the Phased Acquisition Strategy, that prescribes an initial low-rate production phase, intensified testing and operations, and rapid use of test and operations data.

The analysis has employed a model of the early production phase to illuminate key decision variables and their effects on program outcomes. The model identifies how the initial production rate, initial production phase length, and early operational test intensity affect program cost-effectiveness. The model reveals that the PAS approach provides the most cost-effective outcome in programs where (1) design changes cost much more to implement after a system has been produced than on the production line, (2) schedule compression causes resource use so inefficient that costs increase significantly, and (3) program structure minimizes cost increases that vary with program length.

This dissertation has conducted case studies of actual Air Force programs to investigate links between program characteristics and outcomes and to explore how PAS might affect these outcomes. The case studies explore PAS program variations suggested by the theoretical model. The cases studied have program characteristics covering a sufficiently broad spectrum to illuminate partially how design immaturity and program structure influence program outcomes.

Table 22 presents a summary of the case studies and results. Since this sample consists of only three programs, statistical analysis would not provide statistically significant inferences about acquisition strategy effects on program outcomes. These three programs, previous acquisition experience, and the analytical models do, however, suggest some key relationships between acquisition program characteristics and program outcomes.

In terms of the probability of system design immaturity, immaturity

Table 22

SUMMARY OF CASE STUDY IMPLICATIONS

	PROGRAM		
	C-5A	F-111	F-15
Program Characteristics			
Technological advance & design risk	modest	large	moderate
Degree of concurrency	high	high	moderate
Timing of production commitments	very early	moderately early	moderately early
Air Force - contractor interaction	poor	poor	good
Use of test information	poor	poor	good
Actual Program Results			
Speed of aircraft delivery	rapid	moderately rapid	moderately rapid
Design problems	one, dominant	many, minor & major	few, relatively minor
Effectiveness limitations	major	major	modest
Pas Effects			
Aircraft delivery delay	substantial	moderate	moderate
Cost savings, $M	391	30	10
Effectiveness increase	large	very large	modest

appears most likely when

- o large technological advance and design risk prevail,
- o extensive concurrency occurs,
- o production commitments precede adequate design demonstration,
- o tests do not occur and test information does not feed back early in the design process, and
- o the Air Force has only poor visibility of the design process.

In turn, design immaturity leads to

- o costly design modifications, and
- o long-term effectiveness limitations.

The conventional acquisition strategy--through partial concurrency, early production commitments, emphasis on technological advance, and incomplete testing and use of test information--often results in programs characterized by

- o rapid aircraft deliveries,
- o design immaturity,
- o extensive design modifications, and
- o diminished system effectiveness.

On the other hand, PAS--through minimized concurrency, extended low-rate production, and intensified testing and use of test information--appears to generate programs characterized by

- o slower initial aircraft deliveries,
- o increased design maturity,
- o substantially reduced modification costs, and
- o significantly increased system effectiveness.

The magnitude and importance of these diverse costs and benefits

reflect the unique characteristics of each program and the context in which the program evolves. *Slower initial aircraft deliveries* may present serious problems in a war or crisis situation. In peacetime situations, slower deliveries may force the Air Force to rely on obsolete or undependable aircraft for an extended time period. In general, the Air Force seeks to minimize the time required to build up its aircraft inventory and any delay results in costs which usually defy monetization. On the other hand, slower initial delivery, and the other features of PAS, tend to *increase design maturity* of production systems. This means more stability in the design of operational aircraft and more stable demands on the maintenance and support systems. Though clearly a benefit, the stability introduced by increased design maturity results largely in organizational efficiencies which elude direct quantification. The most easily quantified benefit of PAS appears to result from the decreased requirement for system retrofit. When design changes cost much more to do through retrofit than on the production line--either because of the quantity or scope involved--then PAS offers *large modification cost reductions*. The case studies, making conservation assumptions, indicate a lower limit on savings of a few tens of million to a few hundred million dollars; the theoretical analysis also indicates probable savings in this range. The savings magnitude depends directly on the scope of required retrofit. Finally, a PAS approach produces *fewer limited-effectiveness systems*. In a program such as the C-5A, this results in substantial improvements in day-to-day, fleetwide effectiveness over an extended period. Such limitations may restrict operations and increase costs in routine circumstances, and have minimal impacts in crisis situations. In the F-111 and similar programs, however, routine operations and costs may not differ significantly, but wartime effectiveness may suffer extreme degradations. In general, the advantages of a particular acquisition strategy depend on all characteristics of the scenario in which it is evaluated.

The previous paragraph poses the key costs and benefits addressed by this research which a program planner must consider in making program tradeoffs. In terms of effectiveness, PAS requires a decrease in initial aircraft quantity in return for subsequently higher aircraft

performance, reliability, and maintainability. This tradeoff requires the program decisionmaker to choose between short-run and long-run benefits. Program decisionmakers must also select between short- and long-run costs. With the objective of minimizing life cycle costs, the program manager might elect to pursue a PAS approach that raised short-run costs.

Most current policy objectives appear to encourage an acquisition approach broadly consistent with PAS. They generally reflect the above discussion, and recommend pursuing an acquisition strategy shaped to individual programs with emphasis on life cycle effects. Policies do not always agree however, with what happens in practice. Though the F-15, and the prototyped military programs of the 1970s, provide evidence of a trend toward effectively implementing extant policies, other programs, such as the F-15 engine, appear to deviate from current policies. This research does not attempt to investigate the incentives, motives, and organizational obstacles affecting acquisition policy implementation. It does, however, (1) provide a framework for evaluating some advantages of alternative acquisition strategies, (2) illustrate the importance of acquisition strategy in determining long-run outcomes, and (3) identify key tradeoffs and probable costs and benefits of a PAS approach.

B. GENERAL LESSONS

This analysis leads to several general lessons for the conduct of future acquisition programs. These lessons lack the specificity of the results discussed above, but instead provide more general guidelines for structuring future programs.

First, program planners need to direct more attention to the relationship between acquisition strategy and life cycle costs and effectiveness. Policy directives not withstanding, actual acquisition decisionmaking tends to focus on near-term results. Program planners tend to focus more on short-run and relatively certain R&D and production costs than long-run, less predictable O&M costs. Similarly, since systems deliver effectiveness only after the acquisition process has been underway for an extended time, program decisionmakers usually focus more attention on near-term issues than eventual system effectiveness.

Extensive previous research, and this research to a lesser degree, has emphasized the leverage that early decisions have in affecting program outcomes. Thus, it is important for acquisition planners to (1) *avoid underestimating the impact of early decisions* on long-run program outcomes and, (2) *take advantage of early opportunities* to improve life cycle cost-effectiveness.

Second, program planners should pay more attention to selecting flight and production rates on the basis of their effect on program outcomes. In this analysis, flight and production rates serve as two primary acquisition strategy decision variables. Though flight and production rates do vary in actual programs, it does not appear that they serve as decision variables to the extent considered here--production rates appear determined largely by program budgets and flight rates appear based mostly on historical experience. This analysis suggests that life cycle cost-effectiveness may benefit from choices of production and flight rates that produce information while minimizing program commitments. It suggests one technique for gathering operating information rapidly without increasing costs--the lead-the-fleet approach. Though employed in the commercial airliner industry, this approach has had military experience limited primarily to corrective, rather than preventive situations. This approach, and probably others, offers a means of *controlling the costs of acquiring information* about potential system deficiencies which could lead to high modification costs.

Third, the factors which affect production costs deserve more attention and require better understanding. The analysis here has shown that production costs exceed most other acquisition cost components analyzed. It has also suggested that the fixed costs of production-line modifications could be reduced through careful planning of the way in which production capacity is built up. Since achieved production rates often fall short of planned rates, actual production costs may be higher than anticipated because of excess investment in production tooling. Future programs should consider more realistic production-rate targets to reduce the costs associated with excess tooling. Additionally, the process of increasing production rate deserves further study to *manage the transition from low- to high-rate production at*

minimum cost.

Fourth, the case studies provide evidence that the Air Force should maintain a significant role in the design decisionmaking process of new systems. The results do not suggest micro-management by the Air Force but, rather, open channels for providing Air Force input into the major tradeoffs that determine overall system characteristics. In the military system acquisition situation, contractors have few direct incentives for considering the long-run cost-effectiveness of a new system; the military, however, faces the cost-effectiveness characteristics of new systems throughout their operating lifetime. Furthermore, different commands bear different costs and receive different benefits. From an overall Air Force perspective it is essential that *early design decisionmaking reflects the broadest possible long-run Air Force requirements, resources, and constraints.*

Finally, recent acquisition experiences demonstrate a partial trend towards the policies advocated in this study. The F-15 represents one example of program structure relatively consistent with the strategy recommended herein. However, not all recent cases reflect the advocated strategy. Future programs should take advantage of the lessons from previous experiences and this research, and *utilize an acquisition program structure consistent with current policies as tailored to the unique needs of the program.*

Appendix A

DETAILS OF SOLUTION TECHNIQUES

Appendix A presents the approach used to solve this problem. This approach provides an explicit solution for r_2, and two equations in r_1 and Q_1. Let

$$X_1 = r_1$$
$$X_2 = r_2$$
$$X_3 = Q_1$$

and

$$f(X_1, X_2, X_3) = LCC.$$

The first-order conditions for a minimum of f require

$$\frac{\partial f}{\partial X_1} \equiv f_1 = 0$$

$$\frac{\partial f}{\partial X_2} \equiv f_2 = 0$$

$$\frac{\partial f}{\partial X_3} \equiv f_3 = 0.$$

The second-order conditions require the Hessian determinants H_1, H_2, and H_3 to be positive definite.[1]

The first-order conditions, using the previously developed cost functions, are:

$$f_1 = -(\alpha_1 + \alpha_6) \cdot \frac{Q_1}{r_1^2} + \alpha_3 \cdot Q_1 + \frac{\alpha_4}{Q_1} + \frac{(\alpha_5 - OC_1) \cdot Q_1^2 \cdot OH_1}{2 \cdot r_1^2} = 0 \qquad (15)$$

[1]See a text such as Chiang Alpha, *Fundamental Methods of Mathematical Economics*, McGraw-Hill, New York, 1967.

$$f_2 = -\frac{\alpha_1 \cdot (Q_T - Q_1)}{r_2^{\,2}} + \alpha_3 \cdot (Q_T - Q_1) = 0 \tag{16}$$

$$f_3 = \alpha_1 \cdot \left(\frac{1}{r_1} - \frac{1}{r_2}\right) + \alpha_3 \cdot \left(r_1 - r_2\right) - \frac{\alpha_4 \cdot r_1}{Q_1^{\,2}}$$

$$- \left(\alpha_5 - OC_1\right) \cdot \frac{Q_1 \cdot OH_1}{r_1} + \frac{\alpha_6}{r_1} + \beta_1 - \beta_2 = 0. \tag{17}$$

The second-order conditions are:[2]

$$f_{11} > 0 \tag{18}$$

$$\begin{vmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{vmatrix} = \begin{vmatrix} f_{11} & 0 \\ 0 & f_{22} \end{vmatrix} = f_{11} \cdot f_{22} > 0 \tag{19}$$

$$\begin{vmatrix} f_{11} & 0 & f_{13} \\ 0 & f_{22} & 0 \\ f_{31} & 0 & f_{33} \end{vmatrix} = f_{11} \cdot f_{22} \cdot f_{33} - f_{13} \cdot f_{22} \cdot f_{31}$$

$$= f_{11} \cdot f_{22} \cdot f_{33} - f_{13}^{\,2} \cdot f_{22} \tag{20}$$

We can directly solve (16) for r_2, or

$$r_2 = \sqrt{\alpha_1/\alpha_3}\ . \tag{21}$$

---

[2] $f_{12} = f_{21} = 0 = f_{23} = f_{32}$ by inspection of (15), (16), and (17), and using (21).

Multiplying (15) by $Q_1 \cdot r_1^2$ produces

$$- \left(\alpha_1 + \alpha_6\right) \cdot Q_1^2 + \alpha_3 \cdot Q_1^2 \cdot r_1^2 + \alpha_4 \cdot r_1^2$$
$$+ \left(\alpha_5 - OC_1\right) \cdot \frac{Q_1^3 \cdot OH_1}{2} = 0. \qquad (15')$$

Combining terms leads to

$$r_1^2 \cdot \left(\alpha_3 \cdot Q_1^2 + \alpha_4\right) + \frac{Q_1^3 \cdot OH_1}{2} \cdot \left(\alpha_5 - OC_1\right)$$
$$- \left(\alpha_1 + \alpha_6\right) \cdot Q_1^2 = 0 \qquad (15'')$$

Solving for r_1 gives

$$r_1 = Q_1 \cdot \left[\frac{\alpha_1 + \alpha_6 - Q_1 \cdot OH_1 \cdot (\alpha_5 - OC_1)/2}{\alpha_3 \cdot Q_1^2 + \alpha_4}\right]^{\frac{1}{2}}. \qquad (22)$$

Since only positive production rates make sense we use the positive squareroot. Substituting the solution, (21), for r_2 in (17) we have

$$\frac{\alpha_1}{r_1} + \alpha_3 \cdot r_1 - 2\sqrt{\alpha_1 \cdot \alpha_3} - \frac{\alpha_4 \cdot r_1}{Q_1^2} - \left(\alpha_5 - OC_1\right) \cdot \frac{Q_1 \cdot OH_1}{r_1}$$
$$+ \frac{\alpha_6}{r_1} + \beta_1 - \beta_2 = 0$$

Multiplying by $Q_1^2 \cdot r_1$ and changing all signs, we get

$$r_1^2\left(\alpha_4 - \alpha_3 Q_1^2\right) + r_1\left[2 \cdot Q_1^2 \cdot \sqrt{\alpha_1 \cdot \alpha_3} + (\beta_2 - \beta_1) \cdot Q_1^2\right]$$
$$+ (\alpha_5 - OC_1) \cdot Q_1^3 \cdot OH_1 - Q_1^2(\alpha_1 + \alpha_6) = 0 \qquad (17')$$

Using (15″) to eliminate the Q_1^3 term we get

$$r_1^2 \cdot \left(3 \cdot \alpha_3 \cdot Q_1^2 + \alpha_4\right) - r_1 \cdot Q_1^2 \cdot \left[2\sqrt{\alpha_1 \cdot \alpha_3} + (\beta_2 - \beta_1)\right]$$

$$- (\alpha_1 + \alpha_6) \cdot Q_1^2 = 0 \qquad (17'')$$

Finally, we can solve this using the standard solution for the roots of a quadratic equation in r_1 to get the following expression for a positive root

$$r_1 = \left\{Q_1^2 \cdot \left(2 \cdot \sqrt{\alpha_1 \cdot \alpha_3} - (\beta_1 - \beta_2)\right) + \left[Q_1^4 \cdot \left(4 \cdot \alpha_1 \cdot \alpha_3 + (\beta_1 - \beta_2)^2\right.\right.\right.$$

$$\left. - 4 \cdot \sqrt{\alpha_1 \cdot \alpha_3} \cdot (\beta_1 - \beta_2)\right) + 4 \cdot (\alpha_1 + \alpha_6) \cdot Q_1^2$$

$$\left.\left. \cdot (3 \cdot \alpha_3 \cdot Q_1^2 + \alpha_4)\right]^{\frac{1}{2}}\right\} \Big/ \left(6 \cdot \alpha_3 \cdot Q_1^2 + 2 \cdot \alpha_4\right). \qquad (23)$$

Thus, we have an explicit solution, (21), for r_2 and two implicit equations in r_1 and Q_1, (22) and (23). We can use a computer program to vary Q_1 until the solutions for r_1 in (22) and (23) match for a given set of coefficients. Then we can vary the coefficients to explore their effects on r_1, r_2, and Q_1.

Appendix B

DERIVATION OF BASE CASE PARAMETERS

The optimum production rate, 100 aircraft/year, and Eq. (21) in Appendix A imply that $\alpha_1 = \alpha_3 \cdot 10^4$. The large majority of aircraft would probably be produced during the full-scale production phase and, therefore, Eq. (11) divided by the quantity of aircraft, Q_2, produced during this phase would give an estimate of average production cost. Thus, we have

$$\text{Average production cost} \approx \left(\alpha_1 + \alpha_2 \cdot r_2 + \alpha_3 \cdot r_2^{\,2}\right) \cdot Q_2/r_2 \cdot \left(\frac{1}{Q_2}\right)$$

$$= \frac{\alpha_1}{r_2} + \alpha_2 + \frac{\alpha_1}{10^4} \cdot r_2$$

$$= \frac{\alpha_1}{10^2} + \alpha_2 + \frac{\alpha_1}{10^4} \cdot 10^2$$

$$= \frac{\alpha_1}{10^2} + \alpha_2 + \frac{\alpha_1}{10^2} .$$

From our program assumptions, average production cost equals \$10 million. Next, use the assumption that all fixed production costs contribute 30 percent of average unit production cost.[3] Therefore,

$$\frac{\alpha_1}{10^2} = \$3 \text{ million}$$

or,

$$\alpha_1 = \$3 \cdot 10^8 .$$

---

[3]Unpublished data for the F-111A indicate that 30 percent of the production costs consisted of overhead charges. Since overhead expenditures typically depend fairly directly on program length and α_1 captures costs that depend directly on time, this estimate may apply reasonably well to a program such as the F-111.

And, this implies

$$\alpha_3 = \$3 \cdot 10^4$$

$$\alpha_2 = \$4 \cdot 10^6.$$

Typical aircraft operating costs are on the order of a few thousand dollars per hour. For this analysis assume operating cost equals $1,000 per hour and each hour of operating experience reduces follow-on development costs by $2,000.[4] Thus, OC_1 equals $1,000 and α_5 equals $2,000 and the difference, $\alpha_5 - OC_1$, equals $1,000.[5]

One of the basic assumptions places modification costs per aircraft at about 5 percent of unit production cost, or about $500,000. Assume that retrofit changes cost three times as much as production-line changes.[6] For this case, let retrofit costs, β_1, equal $750,000; then production-line modification costs, β_2, equal $250,000 and the difference, $\beta_1 - \beta_2$, equals $500,000.

Next, the follow-on development cost coefficients must be estimated. Using the unit modification costs above, total modification costs would be about $100-$200 million; assume the costs of developing these modifications equal about one-third this amount, or roughly $50 million. Assume the one-year length of the initial-production and follow-on development phase is about optimum. Under these circumstances let the recurring follow-on development costs be $50 million per year; therefore, in Eq. (12), α_6 equals $50 \cdot 10^6$. As described earlier, assume that as the follow-on development schedule is compressed the

---

[4]Air Force estimates of typical variable operating costs range from several hundred to a few thousand dollars per hour. See "USAF Cost and Planning Factors," *Air Force Manual 172-3*.

[5]Note that in Eqs. (12), (13), and other relationships where costs-per-flight-hour appear they must be multiplied by the number of hours per year, 8,760, to convert to costs per year.

[6]A review of available modification cost data for the F-111 program supports this distribution between retrofit and production-line modification costs.

costs decrease, reach a minimum, then increase sharply. Assume that the costs of a one-tenth-year and a one-year development phase are equal; therefore, in Eq. (12) α_4 equals $5 \cdot 10^6$.

Finally, let OH_1 equal 0.01. This means that each aircraft would fly 0.24 hours per day to accumulate operating experience to supplement follow-on development.

Appendix C

C-5A COST ESTIMATING METHODOLOGY

Because of the learning-curve role in costs we define a function, F(x), where

F(x) = relative cumulative cost for x items, given an 80% learning curve slope.

Table 8, in the text, presents values of F(x) in the last column. Estimates of first-unit costs require the value, F(81). Using the learning-curve property, the cost of producing the first original wing, OPC(1), would follow from total original-wing production cost and the value of F(81), or

$$
\begin{aligned}
OPC(1) &= \$891 \text{ million}/F(81) \\
&= \$891 \text{ million}/28.19 \\
&= \$31.61 \text{ million.}
\end{aligned}
$$

Similarly, accounting for learning-curve effects, the cost, RC(1), of retrofitting the first wing would be

$$
\begin{aligned}
RC(1) &= \$794 \text{ million}/28.19 \\
&= \$28.18 \text{ million.}
\end{aligned}
$$

The discussion in the text estimates the cost of installing the redesigned wing on all 81 aircraft, during production, at $1,049 million. Using the same logic as above, the production-line redesigned-wing cost, RPC, of the first redesigned wing would equal

$$
\begin{aligned}
RPC(1) &= \$1{,}049 \text{ million}/28.19 \\
&= \$37.21 \text{ million.}
\end{aligned}
$$

Alternative C-5A scenarios would result in some aircraft being constructed with the original wing, as development activities identify and resolve the wing deficiency. Overall, the program would involve three processes related to the wing:

- production of x aircraft with the original wing,
- production of (81 - x) aircraft with the redesigned wing, and
- retrofit of x aircraft with the redesigned wing.

The cost of the first process, using the learning-curve property, would be as follows:

$$OPC(x) = \$31.61 \text{ million} \cdot F(x) \qquad (29)$$

As discussed earlier, the analysis includes the reasonable assumption that the learning, which occurs during original-wing production, carries over to production-line installation of the redesigned wing. Thus, the production-line costs of the redesigned wing could be calculated as if their learning effects began with aircraft number one, but they incurred production costs only on aircraft number x through 81. Therefore, the second cost component--production-line installation of redesigned wings, on the last (81 - x) aircraft--would be as follows:

$$RPC\ (81 - x) = [F(81) - F(x)] \cdot \$37.21 \text{ million.} \qquad (25)$$

Finally, the following relationship gives the retrofit cost component, given that learning occurs during rewinging but does not transfer over from the production line:

$$RC(x) = \$28.18 \text{ million} \cdot F(x). \qquad (26)$$

Total wing program costs simply equal the sum of these components. Thus, in a case where x C-5A aircraft are produced before redesigned wings become available, the total costs, TC, would follow from

$$\begin{aligned} TC(x) &= OPC(x) + RPC(x) + RC(x) \\ &= [\$31.61 + \$28.18 - \$37.21] \text{ million} \cdot F(x) \\ &\qquad + \$37.21 \text{ million} \cdot F(81) \end{aligned}$$

or,

$$TC(x) = \$22.58 \text{ million} \cdot F(x) + \$1{,}049 \text{ million}. \qquad (27)$$

Figure C1 presents plots showing costs and savings, relative to the actual C-5A program, as a function of the number of aircraft produced with the original wing.

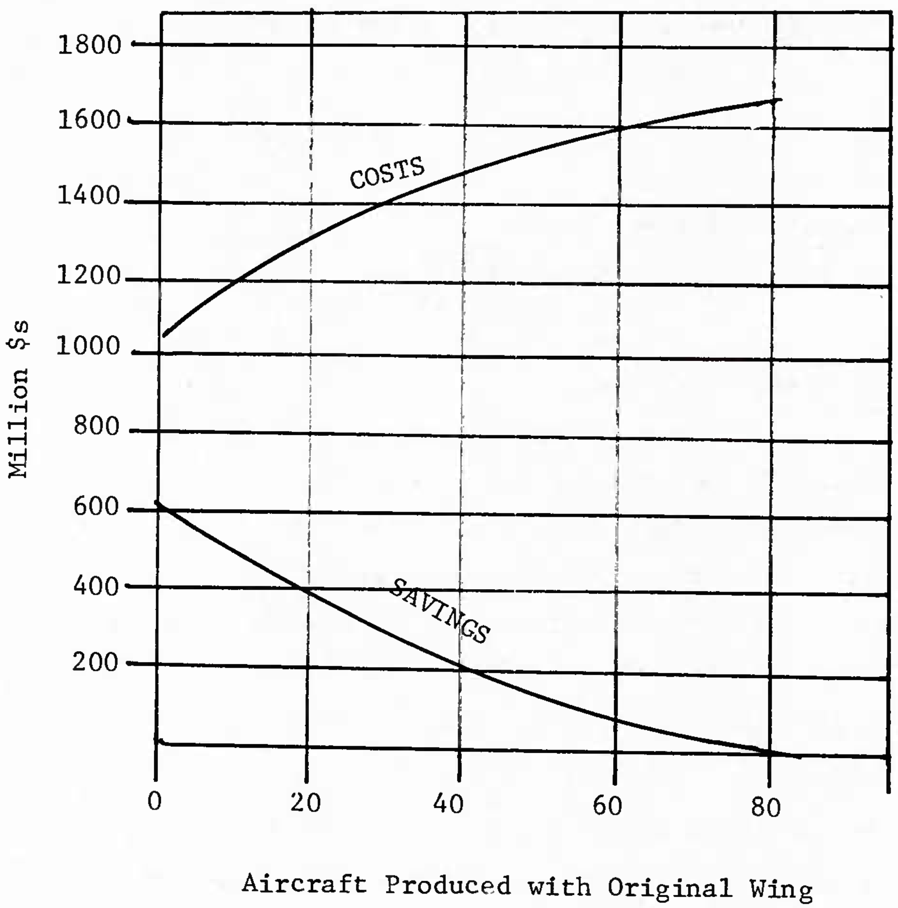


Fig. C1--Wing costs and savings vs quantity of aircraft produced with original wing

Appendix D

F-111 ECP DATA

Table D1 contains the basic ECP data. The columns, identified by an item number at the top, contain the following data:

Item Number	Data
1	ECP number.
2	Subsystem affected by ECP.
3	ECP type: E,R = change in mission C,D = correction of deficiency V = value engineering.
4	ECP date; year, month, day.
5	Total retrofit cost (kits + contractor labor).
6	Total ECP cost (production + retrofit).
7	Number of production aircraft affected.
8	Cost of modifying production aircraft.
9	Number of aircraft retrofit by contractor.
10	Number of aircraft retrofit by Air Force.
11	Total cost of contractor retrofit labor.
12	Total cost of retrofit kits.

Out of the 104 ECPs there were recurring (kits plus contractor labor) cost data for 39 of them. From these data, the number of aircraft which were retrofit by each ECP, and total retrofit costs of each ECP, it was possible to calculate the non-recurring costs for these 39 ECPs as well. From these values the mean ratio of non-recurring to recurring retrofit costs was calculated (excluding ECP 2504 which had a ratio over ten times larger than most values). This ratio was 45.3. This value was used to estimate recurring and non-recurring retrofit costs for the remaining 65 ECPs. Table D2 lists the costs which were estimated, in this way, for these ECPs.

Table D1

ECP DATA

1	2	3	4	5	6	7	8	9	10	11	12	13
0139		PENAD		R660504	213824	10174815469		11947545	0	12		
0219		MTC		R651110	929	91382412		76631	9	7		
0216		PENAD		R660112	75569	1261330654		1011862	9	15		
0324		CREW		P661011	24943	270260331		244099	25	15		
0384		CREW		R660513	11815	114489457		86275	0	12		
0422		ELEC		P670512	50860	236507256		120317	0	12		
0470		PENAD		P661130	15829733	63190502190		52145000	8	73		
0493		CREW		R661209	142438	538789481		420735	12	0		
0495		CREW		R670417	114295	1286627481		1260981	12	0		
0496		ELEC		F660513	21785	107970481		7 292	12	0		0
0497		CREW		F660513	35631	405097457		371712	12	0		0
0498		MECH		F660513	46115	553601462		530606	9	22		
0499		CREW		F660513	25914	100569457		62334	0	12		
0502		CREW		F660513	11649	42914247		22702	0	12		
0503		CREW		F660513	137966	346319481		259545	0	12		
0530		CREW		F660513	23823	92016457		59701	12	0		0
0531		CREW		F661215	7551	21329481		11589	12	0		0
0532		CREW		F670405	6426	37568481		30656	0	12		
0533		CREW		F660506	19156	124250457		90055	12	0		
0596		PROP		P670202	1414	5445481		4937	0	12		
0639		PROP		F660901	7103	-803464443		-947534	7	0		
0703		RADAR		R661202	133183	177707216		62745	0	42		
0746		FLTCT		F670109	24675	168306481		120101	15	0		
0748		CREW		V690109	25400	-44163448		-95641	12	14		
0756		CREW		P671227	15642	29990296		5496	17137		2205	729
0781		ARM		R670421	137972	258928390		119033	54	74		
0796		FUSE		P670130	3909	78832448		78563	4	85		
0845		AVON URT27		F670905	18150	62430481		41628	19	0		
0984		FUSE		F670307	39353	296957435		245347	1	11	11708	21515
0923		AVON TER		F670109	30000	294258457		253170	12	0		
0930		RADARAPO113		9590207T	97956	212778 60		433	0	46		
1037		FUSE		P671201	372600	1132297317		777276	61	95		
1065		PROP		F670929	15000	1160629110		1105629	46	0		
1077		CREW		F671010	9499	30749290		15316	10125			
1092		ECS		R680321	8461	63694355		27775	30	72		
1137		ARM		F671107	36051	81649190		37787	1161			
1173		ELEC		F670525	1793	3979 9		1618	11	12		
1187		CREW		F671102	7610	27705177		17559	25	45		
1203		MECH		P670929	1059	71787458		70708	6	12		
1256		RADAR		P691130	44990	430665 9		106640	20	0		
1258		ECS		P690403	219931	342408152		117216	63118		187144	
1206		AVON AVATT		F670505	373133	6790651247		6244968	9	0		
1267		RADAR P0114		P680229	94119	324276111		223187	6	45		428
1321		AVON COMP		P680719	32393345	57596360164		24373815145		96		
1395		CREW		P671117	76792	3394478		-41520	7	15		
1465		MECH		P680422	10185	17938261		9637	91140			
1493		CREW		P680219	16835	82054110		24939	6	46	3590	[illegible]
1496		FLTCT		F680405	56978	144414475		78352	14	3	43364	5964
1513		FLTCT		F680131	24352	104897304		91675101196				
1537		PROP		P670422	35434	60696190		20231	57	93	34982	0
1558		PROP		F671117	30547	94619379		61054	12	0	1760	21412
1566		CREW		F681122	2161	6965 47		912	30	41	2161	0
1639		FUSE		F680131	453773	972009296		414424	6153		400224	41965
1667		ELEC		P680703	126595	86695190		25777	9153			
1681		PROP		R690217	206996	1194244110		789526	1	0		
1736		ELEC		P681219	99148	163200 24		63287	4	46	25898	17024
1744		PROP		R680628	139133	178557229		32859	5243		108995	16687
1763		MECH		D681021	2680	3388204		-711	6246			
1803		HYD		R680703	22265	38490182		14500	17269		21455	810
1812		ECS		P680636	44595	98101296		49223	11145		38309	4525

Table D1

ECP DATA
(Continued)

1 2	3	4 5	6	7 8	9	10 11	12	13
1813	ARM	R681028	1426736	2690800117	1212652	5218	1349222	12633
1814	ARM	F681210	76091	195143336	69029	7174	51678	6132
1836	AVON IFF	R681101	58478	153221280	71699	17243	48077	5515
1860	CREW	R680523	5940	31838110	24516	2 0	540	5400
1866	FUSE	R681024	74841	433	41637	86 54		
1893	FUSE	F680608	508380	900000302	382020	3123	498040	
1897	CREW	R680607	129055	147059299	5142	17148	61629	55813
1904	MECH	R681010	91373	102469340	19632	6192		
1943	CREW	E680726	4261	9757297	5367	17149	2930	312
1948	CREW	R681101	232416	338213180	109053	8272		
1953	MECH	R681011	50976	80273180	34781	35236		
1979	RADAR	E680527	61242	131594303	39519	2 50		
1999	HYD	D680924	571	1340180	-193	9281		
2029	HYD	E681016	10271	61430298	51234113	57		
2062	FLTCT	C681024	64714	95502206	31129	4 0		
2030	AVON COMM	R690117	40925	65730180	15132	8236	31446	
2091	ELEC	F680822	887417	29946005286	28286002	4 0	830370	57107
2115	CREW	V690120	10361	28852344	-980	24333		
2120	MECH	D681101	8280	7787 47	-493	39308	0	0
2123	CREW	V681122	10910	-141182266	-160440	9222		
2139	CREW	V681219	3506	-24871248	-34566	0122		
2124	ELEC	R690115	97368	138185300	54957	17144	56095	6610
2202	FLTCT	F681025	295658	714996397	203773	19 58	87827	15225
2207	ELEC	R681220	2415	18190106	15775	4 0	2173	242
2235	ELEC	F681213	58216	168474236	23911	65174		
2252	ECS	F690307	96347	565991276	334728107	0		
2263	FUSE	D690507	732549	774334204	29051	37232		
2269	CREW	V690307	18357	31535 70	10272	5 0	1582	1213
2291	MECH	F690502	39803	233999354	186157	6 0		7811
2324	ELEC	F690430	12354	26880 50	10746	6 20	2685	1769
2331	FLTCT	R690804	40743	89671271	33415	6202		
2344	ARM	R690425	5831	13355318	3457	17 56		
2243	FO	F690131	495805	874494256	368404	19208	374250	46439
2379	FLTCT	C690829	34315	63482 24	26251	6 46	15617	2137
2402	FLTCT	R690811	130540	180594 82	4236	20354	80598	3264
2472	MECH	E690609	411699	533864254	109234	19207	251800	41484
2475	PROP	R690829	3756	22704165	15129	9294	3326	307
2498	FLTCT	R690930	23551	31584141	4045	20319	16903	6648
2499	ARM	F690801	33287	77632 70	41673	4 0	30499	1920
2504	MECH	R690918	90652	127681140	19314	29434	22208	2082
2544	ELEC	F690728	5322	7966 70	834	4 0	1979	1215
2593	ELEC	R691229	22727	37336 57	9268	3129	22162	547
2606	ELEC	R700323	8467	46926 37	15109	4 53	4784	1080
2648	FUSE	R700116	85386	111612115	13464	33319		

Table D2

ESTIMATED RECURRING AND NON-RECURRING ECP COSTS

ECP Number	Non-Recurring Costs, $	Recurring Costs, $	ECP Number	Non-Recurring Costs, $	Recurring Costs, $
219	805	17.8	1187	2,990	66.
216	49,398	1,090.	1395	51,629	1,140.
139	169,044	3,732.	1037	83,849	1,851.
384	9,341	206.	748	16,138	356.
496	17,223	380.	1513	4,372	97.
497	28,169	622.	1267	39,570	874.
498	27,379	604.	1092	2,602	57.
499	20,487	452.	1465	1,670	37.
502	9,209	203.	1979	28,512	629.
503	85,355	1,384.	1321	5,125,453	113,145.
530	18,834	416.	1667	28,920	638.
533	15,176	335.	1999	77	2.
639	6,235	124.	1763	403	9.
324	13,246	292.	1866	18,296	404.
470	5,677,648	125,334.	1904	15,151	334.
493	112,608	2,486.	1973	7,172	158.
531	5,970	132.	2029	2,161	48.
703	53,542	1,182.	2062	59,463	1,313.
746	18,537	409.	1948	32,365	714.
796	1,285	28.	2120	956	21.
923	23,717	524.	2123	1,349	41.
596	1,118	25.	2139	949	21.
495	90,359	1,995.	2235	9,276	205.
532	5,080	112.	2115	1,167	26.
781	36,065	796.	930	48,602	1,073.
422	40,209	888.	1681	202,525	4,471.
1173	1,189	26.	2252	25,683	567.
1266	311,288	6,872.	2344	2,252	50.
845	12,787	282.	2263	107,289	2,368.
1065	7,442	164.	2331	7,286	161.
1203	758	17.	1256	31,211	689.
1077	2,387	53.	2648	9,736	215.
1137	7,880	174.			

Appendix E

F-15 ECP DATA

This appendix presents the basic ECP data used in the F-15 analysis. ECP files maintained at the F-15 SPO provide the original data. All costs have been adjusted to 1975 price levels.

Table E1 lists the ECPs by number and provides a brief description of each ECP. Table E2 lists the necessary data associated with each ECP. The Effective Date indicates when the ECP first resulted in aircraft modifications. In some cases I estimated this date based on the number of aircraft retrofit by the ECP. The table shows no cost data for those ECPs included for purposes of estimating effectiveness impacts. Though those ECPs do require expenditures the analysis concentrates on how they affect aircraft effectiveness. The last five ECPs appear to depend more on calendar time than flight time for their generation. The analysis assumes they originate in all scenarios on the same date.

Table E1

F-15 ECP DESCRIPTION

ECP Number	Description
496	Heat exchanger and AMAD modifications
279	Heat exchanger control modifications to improve avionics airflow
293	AIM-7F missile roll rate reductions
497	HUD modifications
515	Armament control changes
316	EWWS modifications to reduce demands on pilot
495	Speed brake/stall warning changes for high angle-of-attack conditions
904	Replace oscillator in radar exiter module
521	Install jet fuel starter/gear box
417	Develop center-line ECM pod carriage capability
705	Add proximity switch to landing gear
615	Modify emergency power system
923	Emergency Cooling System heat exchanger modification
883/995	883 = production, 915 = retrofit; change circuit board coating
846	Armament control set design change
604	AIM-9L missile interface update
573	Retrofit TEWS equipment not installed in production
703	Incorporate high technology ejection seat
627	Wing fuel transfer system modification
1028	Wing modification
674	Combine 10 modules into 5
1026	Engine overspeed protection
450	PEP-2000 production line installation
957	Speedup alignment time of Inertial Navigation System
675	Increase radar solid state memory
730	Incorporate double-density central computer memory in production
751	Replace UHF communication system in production
899	Modify Fire Control System
937	Incorporate Programmable Signal Processor in production

Table E2

F-15 ECP DATA

ECP Number	Effective Date	Retrofit		Man-Hours	Production	
		Non-recurring Costs, $	Recurring Costs, $		Non-recurring Costs, $	Recurring Costs, $
496	9-75[a]	---	6,877	28	856,624	1,113
279	11-75	380,970	5,407	40	---	344
293	11-75	91,182	3,234	68	91,183	2,670
497	11-75[a]	50,439	5,815	2	523,231	12
515	6-76	94,327	221	59	646,156	107
316	8-76	---	2,533	48	526,439	1,502
495	8-76[a]	71,871	7,186	240	153,252	1,803
904	8-76	---	63,604	2	---	---
521	11-76[a]	72,018	1,560	70	344,408	1,238
417	12-76[a]	111,752	3,976	225	1,191,536	4,771
705	1-77	62,626	2,180	240	269,688	1,912
615	2-77	---	2,144	220	693,292	2,144
923	6-77	---	663	---	---	---
883/995	6-77	11,344	1,613	65	---	455
846	11-77[a]	---	235	232	294,463	235
604	12-77	645,455	7,900	51	2,669,091	10,279
573	3-78	---	---	---	---	---
703	4-78	116,559	161	145	1,553,839	-8,402
627	6-78	69,936	1,563	84	303,361	2,227
1028	10-78	97,479	1,085	100	---	---
674	11-78	---	---	---	---	---
1026	11-78	57,143	4,230	200	743,697	4,496
450	6-79[a]	---	---	---	---	---
957	3-80[a]	---	---	---	---	---
675[b]	4-78	3,162,750	263	22	2,274,934	-15,126
730[b]	10-79[a]	---	---	---	---	---
751[b]	5-78[a]	---	---	---	---	---
899[b]	3-78	92,437	1,460	7	---	1,460
937[b]	6-79[a]	---	---	---	---	---

[a]These Effective Dates are estimates based on ECP effectivity.

[b]ECP is calendar-time dependent.